

Characterization of Tire Wear Particulates

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CHARACTERIZATION OF TIRE WEAR PARTICULATES

by

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November 1981
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16. ABSTRACT This report describes results from laboratory test conditions to collect and characterize tire wear particulates as produced by the operation of passenger car tires. The tests were performed on a single radial tire (DR78-14) and a single bias tire using the capabilities of the Calspan Tire Research Facility (TIRF) that features a flat test surface consisting of a coated steel belt that simulates the friction properties of actual road surfaces. Tires were also tested under typical load and inflation pressure conditions. The general conclusions were: a) Airborne rubber particulates were produced in an extremely small quantity. b) The bulk of the collected airborne particulates were identified as contaminant debris. c) Tests on the radial tire produced a particle size distribution with a medium particle diameter about one-half of that produced by identical tests on the bias tire.		
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FOREWORD

This report is submitted in fulfillment of EPA Contract No. 68-03-2781. This report has been reviewed by the Emission Control Technology Division, U. S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U. S. Environmental Protection Agency, nor does the mention of trade names or commercial products constitute endorsement or recommendation for use.

ABSTRACT

The principal objectives of this research program were to collect and characterize tire wear particulates as produced by the operation of passenger car tires under the controlled test conditions of the laboratory. Additionally, sufficient quantities of both the airborne particulates ($<30\text{ }\mu\text{m}$), and the non-airborne particulates were to be collected to permit bioassay tests to be performed by the EPA on the individual samples.

Tests were performed on a single radial tire (DR78-14) and a single bias tire (D78-14) using the capabilities of the Calspan Tire Research Facility (TIRF) that features a flat test surface consisting of a coated steel belt that simulates the friction properties of actual road surfaces. Tires were tested under typical load and inflation pressure conditions using a TIRF schedule of applied wheel torque and wheel steer (slip) angle that results in normal rates of tire wear and a uniform cross-tread wear. Tires were operated within a special enclosure fabricated for the purpose of facilitating a gross separation of the nonairborne particulates from the airborne particulates that were collected by high volume samplers and a cascade impactor. Particulate characterization was accomplished using the techniques of the optical and the scanning electron microscope.

Airborne rubber particulates were produced in an extremely small quantity irrespective of the tire construction used or the relative severity or the type of wear condition that was imposed on the tire. The bulk of the collected airborne particulates was identified as contaminant debris, principally stainless steel. Tests on the radial tire produced a particle size distribution with a median particle diameter about one-half of that produced by identical tests on the bias tire. Consequently, the latter is responsible for the generation of smaller quantities of airborne particulates than the former.

Samples of the collected particles were sent to EPA for bioassay (Ames) tests but difficulties (for now) have been encountered in dissolving the particulates.

This report was submitted in fulfillment of Contract No. 68-03-2781 by the Advanced Technology Center of Calspan Corporation under the sponsorship of the U. S. Environmental Protection Agency. This report covers the period February 5, 1979 to April 4, 1980, and work was completed as of May 9, 1980. This report is identified as contractor's Report No. 6500-T-1.

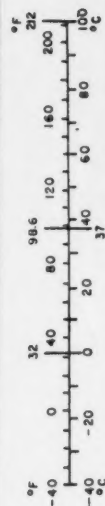
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
in ²	square inches	6.5	square centimeters	cm ²
ft ²	square feet	0.09	square meters	m ²
yd ²	square yards	0.8	square meters	m ²
mi ²	square miles	2.6	square kilometers	km ²
	acres	0.4	hectares	ha
MASS (weight)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
VOLUME				
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft ³	cubic feet	0.03	cubic meters	m ³
yd ³	cubic yards	0.76	cubic meters	m ³
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* 1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price \$2.25, SD Catalog No. C13.10:286.

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
AREA				
cm ²	square centimeters	0.16	square inches	in ²
m ²	square meters	1.2	square yards	yd ²
km ²	square kilometers	0.4	square miles	mi ²
ha	hectares (10,000 m ²)	2.5	acres	
MASS (weight)				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
VOLUME				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
m ³	cubic meters	0.26	gallons	gal
m ³	cubic meters	35	cubic feet	ft ³
m ³	cubic meters	1.3	cubic yards	yd ³
TEMPERATURE (exact)				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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SECTION I

INTRODUCTION

Estimates made of the quantity of tread rubber annually worn from vehicle tires in the United States place the weight in the order of 5×10^8 kg (1, 2)*. This debris represents a potential source of pollution especially with regard to that fraction which remains airborne for an appreciable length of time. Typically, this airborne category includes particles which are less than ≈ 20 μ m in diameter. Within this airborne fraction, the potential health hazard would be greatest with particles less than about 15 μ m in diameter since these are able to penetrate and be retained in the human respiratory system. Thus two considerations are involved: (a) the weight fraction of this tire debris that is found in particulates of a respirable size and (b) the mutagenicity of these particulates.

A large number of studies aimed at answering question (a) above have been reported in the literature within the last decade. These efforts have included passive-type of outdoor studies in which airborne particulates were sampled in the proximity of busy thoroughfares and within the confines of tunnels (see for example reference 2) as well as active-type of tests wherein particulates were collected in the wake of tires on vehicles operated over various types of roadways (see for example reference 3). In addition, indoor laboratory studies have been performed to take advantage of the controlled test conditions which can thereby be achieved in producing tire wear particulates (see for example references 1 and 4). An excellent survey report (5) summarizes procedural details and the test results obtained from various outdoor and indoor studies related to the collection, identification and sizing of tire wear particulates.

In contrast to the extensive literature on the physical characteristics of the wear particulates, there is a dearth of information on the possible mutagenic properties of these same particulates.

A major criticism directed at laboratory-type tire wear programs has been the inability to simulate real world conditions as they exist on the roadways. To a large extent, the test apparatus and the experience in tread wear studies available at Calspan tend to nullify many of these objections. The TIRF flat-bed machine (6)** provides a flat, textured test surface similar to a type of a real world roadway. Steady state and dynamic forces, torques, speeds and steer angles can be applied to the test tire in a programmed manner. In addition, tire tread wear schedules have been developed (7, 8) that can simulate a variety of tread wear rates spanning the range from low to normal to severe with tire tread surface textures representative of road worn tires.

* Numbers in parenthesis designate references listed at the end of the report.

** See also Appendix C.

The test program described in this report was undertaken to collect and characterize tire wear particles under simulated roadway conditions including surface texture, skid number, vertical load, wheel torque, slip angle and speed. Tests were performed on a low wear rate (radial ply) tire and a high wear rate (bias ply) passenger car tire. The test effort was divided into two phases. Phase A comprised steady-state tests of (a) straight-rolling tire operation at 96 km/h (60 mph) and (b) cornering (constant slip angle) operation at 40 km/h (25 mph) for the purpose of determining the effect of test conditions on types of wear particulates produced. Phase B tests were designed to simulate normal wear conditions by operating the test tires at a constant speed of 88 km/h (55 mph) but with time-varying, simultaneous inputs of both slip angle and wheel torque.

The tires were operated within a multichambered enclosure equipped with two high-volume samplers ("hi-vols") and a single, six-stage cascade impactor. Use of the enclosure served two important functions: (a) to provide effective particulate separation, in a gross sense, by size through the incorporation of a settling chamber and (b) to reduce the loss of wear particulates.

This report discusses the details of the instrumentation, the test procedures and the results that were obtained. Particulate analysis was restricted to size and material characterization. Bioassay testing of the particulates was performed by the EPA, and the results thereof are outside of the scope of the program described in this report.

Included within the scope of the program was a requirement to estimate the characteristics of truck tire emissions as compared with emissions from passenger car tires considering the differences in size, construction, tread rubber compounding and vehicular use patterns. Results of this study, based on the application of engineering judgment and the extrapolation of experimental data for passenger car tires, are presented in Appendix A.

SECTION II

CONCLUSIONS

The itemized conclusions that follow apply to the specific studies completed during the course of this program. Experimental data were obtained for one specific radial-ply tire (DR78-14) and one specific bias-ply tire (D78-14) with all the testing performed on the Calspan Tire Research Facility.

The more significant findings follow:

- Airborne rubber particulates ($\leq 30 \mu\text{m}$) were produced in extremely small quantities irrespective of tire construction or the type and severity of the imposed wear condition.
- Airborne particulates were mainly contaminant material with stainless steel the chief constituent. These particles are generated by the operation of the stainless steel belt used on TIRF.
- Tests on the bias tire produced a significantly smaller mass of airborne particulates than did similar tests on the radial tire.
- Based on the analysis of the floor samples in the collection chamber, the bias tire produced a median particle size approximately twice that of the radial tire with both tires operating under identical test conditions.
- There appears to be an absence of rubber particles in the approximate size range between $1 \mu\text{m}$ and $10 \mu\text{m}$.
- Rubber particle size distributions produced during TIRF tests (no simulated road dust used) are like those reported for on-vehicle tire tests performed on highways.
- The introduction of a roadway "dust" (cornstarch) decreased the mean size of the very large, nonairborne rubber particles.
- An engineering assessment of expected truck tire wear emissions indicates that, compared with passenger car tires, the wear rate will be comparable, with the particle size distribution favoring the smaller particles.

SECTION III

RECOMMENDATIONS

Reflecting insight and experience acquired in performing the experimental studies described in this report, the following itemized recommendations are offered as worthy of consideration in extending the scope of the present study. Principally, the purpose of these suggestions is to confirm the relative scarcity of the rubber particles in the very small size, airborne range by broadening the range of test variables.

- Satisfactory simulated roadway surfaces, combining micro- and macro-texture characteristics representative of actual road surfaces, should be developed for TIRF.
- "Dusts", other than cornstarch, should be investigated which will be compatible with TIRF operations and facilitate a workable method for separating these dusts from the wear particulates.
- A larger sample of passenger car tires should be tested to explore the effects, if any, of different tread compounds on the size distribution of wear particulates. For similar reasons, different tread patterns should also be tested including tires with the bulk of the tread rubber worn away.
- Tests of much longer duration should be planned to permit the collection of larger samples in the particle size range below about 20 μm .
- The loss of very small particulates during a test is a potentially major problem whose magnitude is not known. The use of tracer techniques to quantify this problem should be explored.
- Effective methods for in situ separation of the stainless steel debris from the rubber particulates should be investigated to facilitate size analyses of the airborne rubber particles.
- The characterization of wear particulates produced by truck tires should be attacked experimentally.

SECTION IV

DISCUSSION

A. Preliminary Investigations

1. Selection of the Tire Sample and the Test Conditions

The specific tire sample selected for these purposes was one judged to be representative of in-use automobile tires in terms of size, construction and tread rubber compounding. Two tire constructions were chosen, the radial-ply tire and the bias-ply tire. Because of construction differences that affect cornering stiffness and tread "squirm", the radial tire is characterized by a significantly lower tread wear rate and rolling resistance than an equivalent size bias tire operated under the same test conditions. Rubber compounding is also different between these two constructions with the radial tire using considerably more natural rubber.

A DR78-14 tire (General Dual Steel II)* was selected in the radial construction since it represents a popular size that is used extensively on current model compacts. With the present down-sizing trends of cars, this tire size should see continued, extensive use. A D78-14 bias tire (General Jumbo 780)* was selected to provide a high wear rate tire to contrast with the lower wear rate radial. In the current passenger car tire market, the bias tire is sold only as a replacement. A total of two radial tires and two bias tires was purchased. One set was used for preliminary check tests, and one set was used for the final test runs.

General test conditions were explicitly defined in the contractual statement of work. Two types of tire wear conditions were stipulated: (a) steady-state, highway-type of operation (no cornering) at a speed of 96 km/h (60 mph) and (b) steady-state cornering at 40 km/h (25 mph) with the tires subjected to vertical, longitudinal and lateral forces consistent with those experienced in vehicular applications. In addition, it was required that for each of the above two test conditions, a sufficient quantity of particulate debris, airborne and nonairborne, be obtained to perform five Ames tests on each sample. An individual sample of approximately one-half gram was estimated as adequate for this purpose.

Table 1 summarizes, in a quantitative manner, the details of the test program that was designed to fulfill the requirements of the contractual work statement. Tire test conditions were based on design data, conventional practices and test data. Design load rating for the D78-/DR78-14 tires (load range B) is 4982N (1120 lb) at an inflation pressure of 165 kPa (24 psi). Since it is common industry practice to operate tires at about 80% of design load, a test load of 3985N (896 lb) was selected. Wheel torque figures were obtained by interpolating

* The choice of the manufacturer and tire brand was arbitrary.

TABLE I
Test Tire Sample and Test Conditions for Phase A

Test Tires	Item	Straight Rolling	Cornering
• Bias Ply, D78-14* • Radial Ply, DR78-14** • Maker: General • Tread Design: Ribbed Conventional Highway • Rim Size: 5.00 x 14	• Inflation Pressure, Cold, kPa (psi) • Vertical Load, N (lb) • Roadway Speed, km/h (mph) • Slip Angle, deg. • Camber, deg. • Wheel Torque***, N-m (ft-lb) • Test Duration (est.), min.	165 (24), Capped 3985 (896) 96 (60) 0 0 108 (80), D78-14 99 (73), DR78-14 120	165 (24), Capped 3985 (896) 40 (25) 3.0 (D78-14), 2.7 (DR78-14) 0 47 (35), D78-14 41 (30), DR78-14 90

*General Tire Jumbo 780

**General Tire Dual Steel II

***Wheel Torque Produced Driving Traction

available test data on actual measured torques taken with vehicles operating at steady state conditions on a test track (9). The lesser wheel torque indicated for the radial tire reflects its lower rolling resistance relative to the bias tire.

For the cornering tests, wheel slip-angle settings were calculated assuming a 15940-N (3600 lb = 4 x 896 lb) vehicle operating in a 30.5-m (100 ft) radius circle at a speed of 40 km/hr. A further approximation was made that each vehicle tire contributed equally to the total side force required to maintain the circular path. Typical tire cornering coefficients for the D78-/DR78-14 tires operating at specified load and pressure conditions (10) were used to calculate the necessary slip angles. Since radial tires are characterized by larger cornering stiffness coefficients, a smaller slip angle is required to achieve a given lateral force for the radial tire than for the bias tire.

Test duration was estimated from the time required to produce one-half gram of airborne ($<30\text{ }\mu\text{m}$) particulates for bioassay studies (Ames tests). Tire wear rates were based on previous Calspan experience (7) and available data on the relative fraction of the total mass of rubber particulates that constitute the airborne material (1). Each test was designed to be performed on a dry, flat roadway consisting of a medium-grit, Safety-Walk* surface stoned to a wet skid number of 30. Each new tire was preconditioned by two hours of operation at 80 km/h (50 mph) on a 1.2 m (4 ft) diameter drum at an equivalent load.**

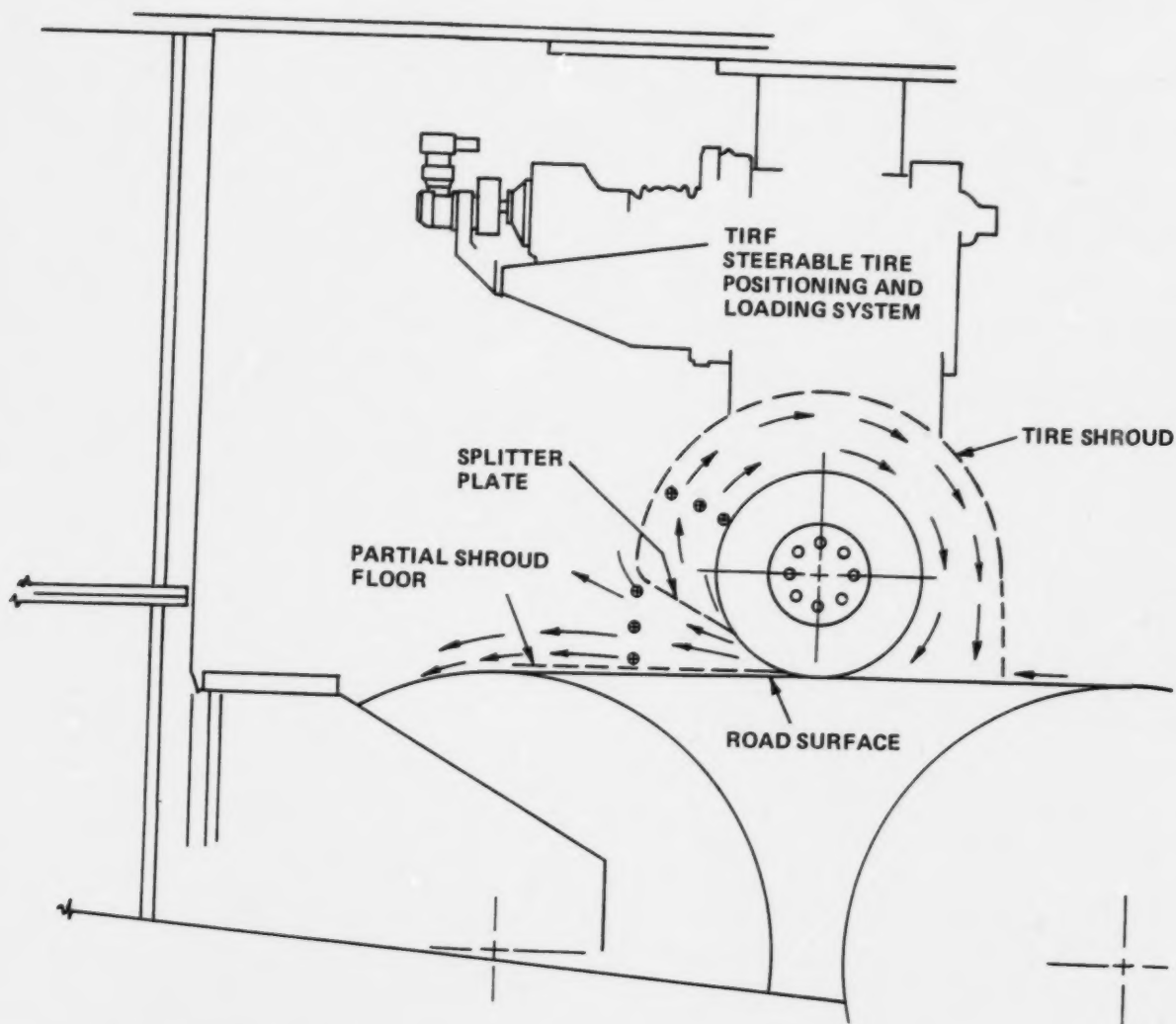
2. The Particulate Collection Chamber

The design and fabrication of an enclosure for the tire under test was essential to the collection of the airborne and nonairborne wear particulates. This enclosure had to fulfill three important functions: (a) reduce to minor proportions the loss of the wear particulates, (b) provide effective separation between particulates less than $\approx 30\text{ }\mu\text{m}$ and those larger than this size, and (c) act as a mounting base for the particulate sampling instrumentation. To provide a rational design basis for such a collection chamber, some simple tests were performed to obtain data on the flow field in the proximity of a shrouded, rotating tire operating on the moving TIRF roadway.

Preliminary flow survey studies were made using an available spare DR78-14 tire mounted on the TIRF machine and fully enclosed within an existing aluminum shroud modified with an added splitter plate. This configuration is shown schematically in Figure 1. To determine the details of the flow field, tests were performed on the straight-rolling tire operating at 96 km/h (60 mph) and an applied driving torque of 95N-m (70 ft-lb). Airflow velocities were measured

* 3M Company.

** The load required to produce the same tire deflection on a drum as that experienced on a flat surface.



⊕ DENOTES LOCATIONS AT
WHICH FLOW VELOCITY
MEASUREMENTS WERE
MADE

Figure 1 SCHEMATIC DESIGN OF AN EXISTING SHROUD ASSEMBLY MODIFIED
FOR PRELIMINARY FLOW FIELD INVESTIGATIONS ON TIRF

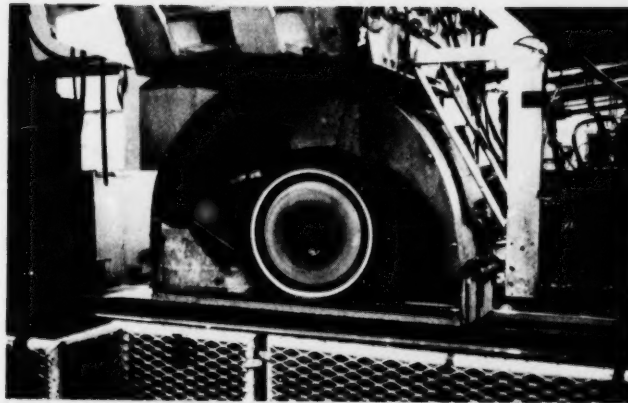
using a hot-wire anemometer that was inserted at selected locations within the enclosed shroud and across the flow exit (see • symbols in Figure 1). From these measurements, approximate flow rates within the shroud annulus and through the exit aperture were calculated. Small segments of a sticky-surfaced paper were strategically placed on the inside surfaces of the shroud perimeter and on the shroud floor at the exit to define visually the general particle deposition patterns in the turbulent flow.* Arrows drawn in Figure 1 indicate the direction of the main flow. Figure 2 shows photographs of the shroud/splitter plate assembly as it was installed on the TIRF facility. Note (Fig. 2) that there is no floor in the shroud forward of the tire contact patch.

From the flow field data and observations based on a cursory microscopic analysis of the particulate debris on the adhesive papers, the induced flow velocities were judged to be quite high, especially in the proximity of the roadway and the tire surfaces. The corresponding induced volumetric flow rates were found to be comparable to the anticipated sampling rates of the particle collection devices to be used ultimately in the collection chamber of the final enclosure design. Thus, it was possible that some finite fraction of the particulate material could be entrained in the induced flow field and lost either to the chamber walls by turbulent deposition or due to entrainment in the boundary layer of the road surface beneath the floor of the chamber.

Based on the data of the flow field survey taken within the shroud, design criteria were formulated and incorporated into the development of a particulate collection chamber that is shown schematically in Figure 3. The chamber is a single integral structure consisting of a tire shroud, the main collection chamber and a secondary collection chamber. A splitter plate extends the width of the shroud and functions to inhibit the entrainment of particulates within the shroud by directing the induced flow into the main chamber. A floor panel extends beneath the entire shroud and main chamber except for the aperture necessary to permit the tire to contact the roadway. A subfloor beneath the main chamber floor provides access to the secondary chamber. Three-inch thick aluminum hexcel honeycomb** extends across the entire areas of the main and secondary chambers. Its purpose is to straighten the airflow and thus create a uniform laminar flow ahead of the sampling devices. A detachable front panel completely seals the assembly from the ambient air except at the tire contact-patch aperture and at the inlet to the secondary chamber. The basic structural materials are plywood and sheet metal. All nonmetallic inside wall surfaces are covered with an adhesive-backed, light-gage aluminum foil to achieve smooth surfaces that are not subject to electrostatic charging. Internal corners at all critical locations are rounded to inhibit local flow stagnation and vortices, both of which conditions are conducive to undesirable deposition of airborne particulates.

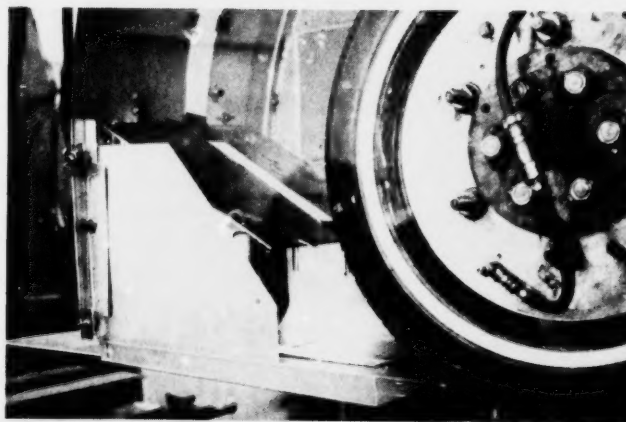
* Extremely small particles would not impact, of course, but these were not of interest in this purely visual assessment.

** The individual hexcel measured approximately 9.5 mm (3/8 inch) across the flats.

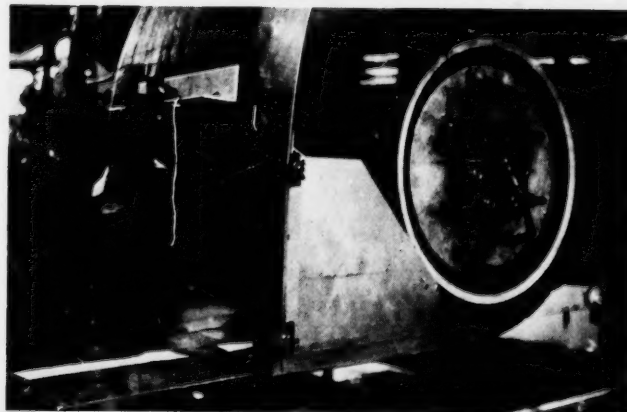


The Shroud/Splitter Plate Assembly During a Test

(Note: The side panel is clear plastic)



Close-Up View of the Splitter Plate and Partial Shroud Floor



Close-Up View of the Flow Exit Area Surveyed with the Hot-Wire Anemometer

Figure 2 PHOTOGRAPHS OF THE MODIFIED SHROUD CONFIGURATION AS INSTALLED ON THE TIRF FACILITY AND USED FOR THE STUDY OF TIRE/ROADWAY INDUCED AIRFLOW

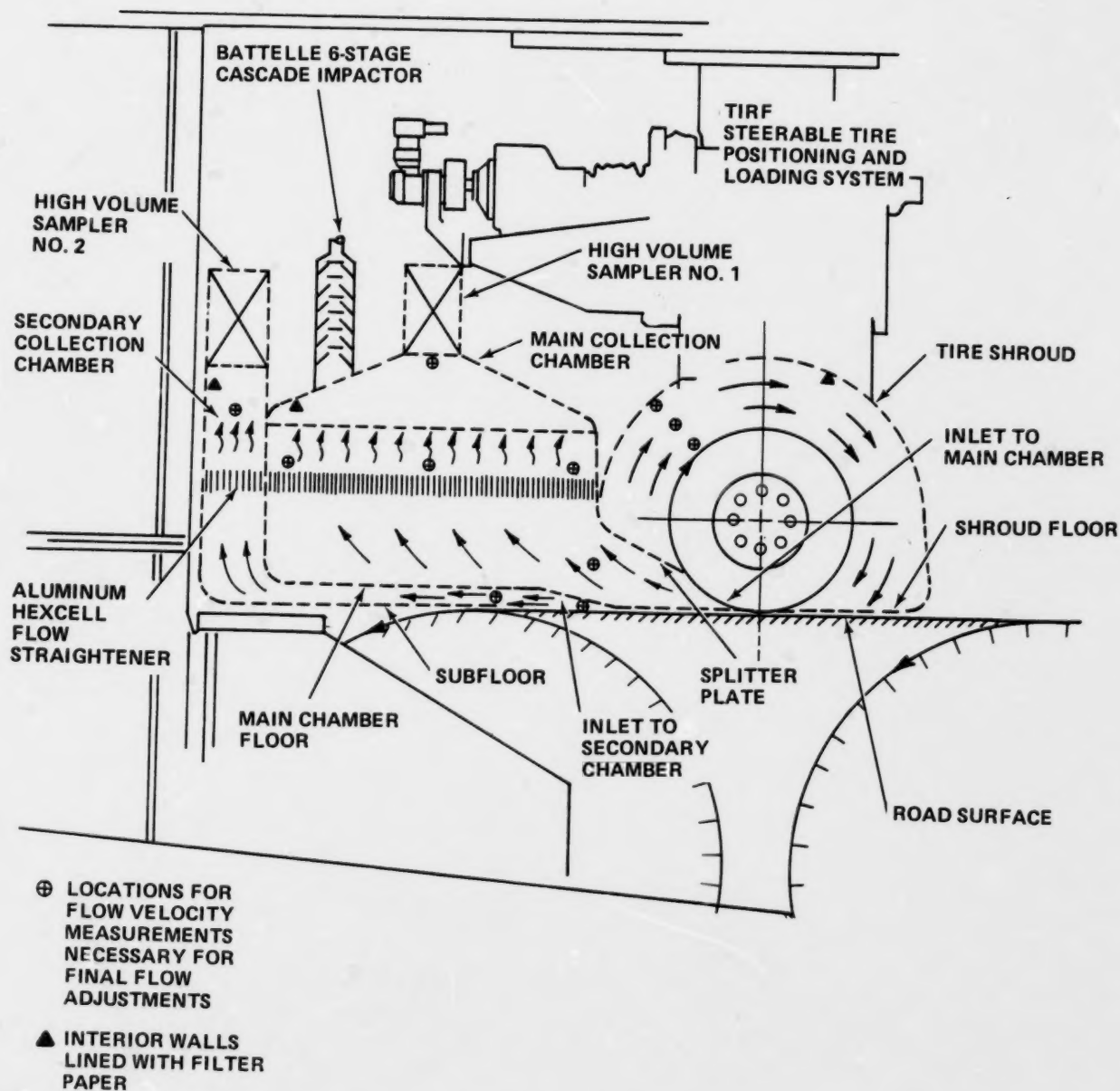


Figure 3 SCHEMATIC DIAGRAM OF THE PARTICLE COLLECTION CHAMBER AND SAMPLING DEVICES AS INSTALLED ON TIRF

The main chamber is approximately 0.46 m (18 in.) deep and 1.02 m (40 in.) wide. A high volume sampler is located centrally at the top and accommodates a 20.3 cm x 25.4 cm (8" x 10") filter upon which the particles are collected. This particulate collection system is designed to acquire sub-30 μm particulates using the principle that selective separation can be achieved, in accord with Stokes' law, by the imposition of a suitable velocity on the particle-laden flow. To establish the desired ambient flow velocity of approximately 3 cm/sec in the upper regions of the chamber, it was calculated that a volumetric pumping rate of 0.8 to 1.0 m^3/min would be required. Flow rates were adjusted in the course of checkout tests to optimize the collection efficiency of particles with equivalent diameter $\leq 30 \mu\text{m}$. A six-stage cascade impactor (Battelle) was mounted also atop the main chamber. Its function was to permit a measurement of the particle size distribution for the sub-30 μm class of particulates.

Preliminary flow field studies with the simple shroud suggested that a finite fraction of the total particulate debris from the tire would be lost beneath the floor of the main chamber because of the relatively high flow velocities in the tire/roadway boundary layer. Consequently, a secondary chamber, equipped with a high volume sampler, was added for the purpose of drawing off this flow (with its entrained particulates) from the road surface as it expands into the inlet portion of this chamber. The volumetric flow rate of this second high volume sampler was adjusted to equal the ram component of the air entering beneath the floor of the main chamber. The addition of the secondary chamber effectively reduced particulate losses and enhanced the collection efficiency of small particulates within the main chamber by the balancing of the flow rates of the high volume samplers.

A photograph of the completed particulate collection chamber and associated instrumentation, installed on the TIRF machine, is shown as Figure 4. The entire side panel has been removed to show the internal configuration. During test operations a gap of approximately 5 mm (0.2 in.) was maintained between the roadway surface and the bottom of the chamber. Because the loaded radii of the radial and the bias tire differed by approximately 7 mm (0.3 in.), the clearance above the roadway had to be made adjustable to accommodate each tire construction. Maintaining a minimum safe clearance was important in the attempt to minimize the loss of the small, entrained particulates.

B. Tire-Wear Tests, Phase A

1. Test Details and Results

The basic test program was planned to consist of a total of four test runs at the conditions shown in Table 1. These four runs were to be comprised of straight-rolling and cornering tests on the bias and the radial tires. As a first step, the rather large and bulky collection chamber was fitted to the TIRF machine to check the mechanical clearances and the enclosure dynamics related to steer angle motions, mechanical vibrations and resonances associated with machine operation.

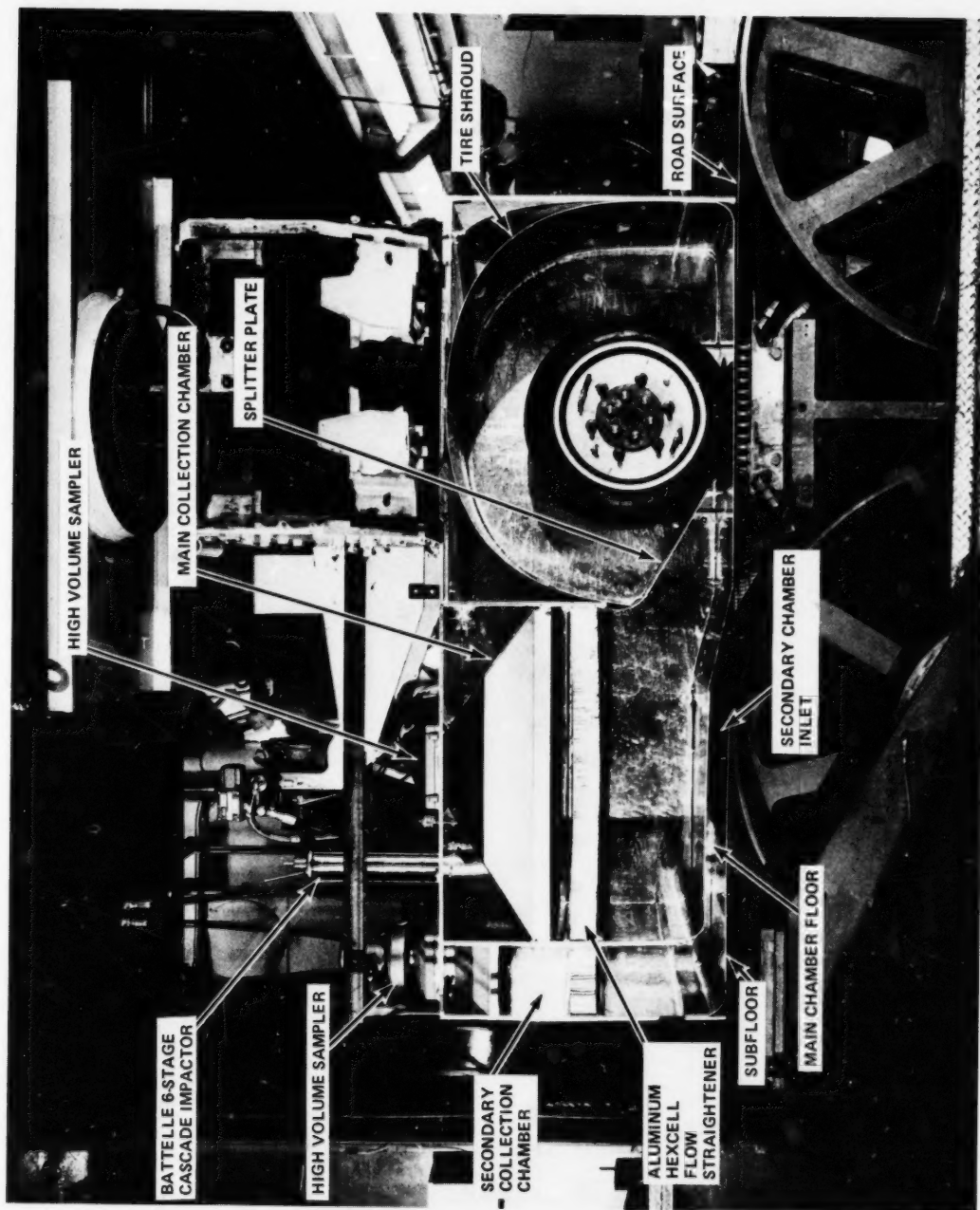


Figure 4 PARTICULATE COLLECTION CHAMBER INSTALLED ON TIRF (SIDE PANEL REMOVED)

At this time the collection chamber was fitted with a full side panel (see Figure 4) of plexiglass to be used for checkout purposes only. This panel was pretapped at various strategic locations (see Figure 3) to accommodate a hot-wire anemometer probe to gather flow velocity data required to adjust the high volume sampler flow rates. These measurements were made with the roadway and the tire operating at the proper speeds but not in physical contact with one another to avoid the possibility of damage to the fragile probe by the larger particulates. The principal reason for the use of a transparent side panel was to permit flow visualization studies to be made using photographic techniques in conjunction with a "smoke" tracer. By injecting the tracer in the area of the tire patch, it was hoped to follow the path of the tire wear debris that was airborne. Despite the use of different types of chemical smoke generators, the attempts at flow visualization were unsuccessful because of the large turbulence in the flow field around the tire. Upon leaving the injector, the smoke was almost instantly dissipated, becoming invisible.

A brief preliminary checkout run (run no. 1) was planned to ascertain that the equipment was functioning properly and that the sub-30 μm particulates were being collected. In addition, the mass rate of generation of the airborne wear particulates was sought so that a reasonable estimate could be made of the test times needed to produce the necessary quantity of material for the bioassay tests. For run no. 1, the high volume sampler flow rates were adjusted to proper values and preweighed filters were installed in the two hi-vol samplers. The collection chamber surfaces were lined with filter paper.

A project D78-14 bias tire was installed on TIRF, and a straight-rolling ($\alpha = 0^\circ$) run was made for a period of one hour at a load of 3985N, a speed of 96 km/h and a driving torque of 95 N-m. Post-test examination of the filters lining the chamber floors showed appreciable amounts of wear debris with many pieces taking the form of irregularly-shaped rolls 3 to 9 mm in length. Some strands of rubber were up to about 50 mm in length. Filters from each of the samplers had a light grayish coating. As shown by microscopic analysis, the particulates were in the proper size class (≈ 2 to 30 μm). Most importantly, the change in weight of the filters was negligibly small as measured on equipment with a resolution of about 10 mg. Based on an estimated tread wear rate for this condition, it was calculated that about 4 grams of rubber particles should have been generated in one hour. If 5% of these rubber particles were in the airborne category (2), a total of 0.2 grams should have been produced. Even with a collection efficiency as low as 5% for each sampler, a change in the weight of the filters should have been detectable. These results indicated the impracticality of collecting a 0.5-gm sample of airborne particles using the test methods of run no. 1.

The tread surface of the test tire had a coarse and tacky feel to the touch. This condition is common to tires operated on steel drums/rolls and also to many tires tested on the TIRF Safety-Walk roadway surface. In contrast, most tires operated on outdoor concrete or asphalt roadways are characterized by a tread surface texture that feels smooth and nontacky.

In the effort to improve collection efficiency of small particulates, run no. 2 was made with both of the high volume samplers operating at their maximum flow rate. The Battelle impactor was installed for this run at the top of the main collection chamber. All units were operated during the test which was made at the same test conditions as used in run no. 1 except that the test duration was reduced to one-half hour. The results in all respects were identical to the first run. Because the cascade impactor uses teflon filter material (rather than the fibrous silica filters used in the samplers), it was convenient to analyze the composition of the small airborne particulates with the SEM. These small particulates were found to be primarily stainless steel.* Results from run no. 2 appeared to indicate that the samplers were collecting such small particulates as were there to collect.

A logical concern arose concerning the possible deposition of the small particles on the extremely large surface areas of the hexcell flow straighteners. Run no. 3 was made as an exact repeat of run no. 2 except that the aluminum honeycomb was removed. No discernible difference could be detected between the quantity and type of particulates collected on runs no. 2 and 3.

As a next step in the quest for the elusive small particulates of rubber, a test was made to collect as much of the debris as possible as soon as it left the tire by attempting to achieve a test condition approaching isokinetic sampling. For this purpose, the splitter plate was removed from the enclosure, and a solid vertical wall was used to isolate the tire shroud from the main chamber (Figures 4 and 5). A centrally-placed aperture was made in this partition to accommodate the filter-tray assembly from a standard high volume sampler. A rectangular converging nozzle was fitted to the filter tray. The inlet to the nozzle was shaped to provide a very close fit to the tire at roadway/tire interface at the aft end of the tire contact patch. A flexible hose was routed from the filter tray, through the side panel of the chamber and to two high-volume blowers from an industrial vacuum system. While the flow rate of this arrangement was not measured, it was known to be larger than that of the standard high volume sampler operating at maximum capacity. Since there was no flow into the main chamber, the only other sampler operating was that on the secondary chamber. The bottom surface of the nozzle was lined with filter paper.

Test run no. 4 used the exact same conditions as the two previous runs. Post-test examination of the filter from the sampler equipped with the nozzle showed little difference from prior tests except for a quantity of visibly larger particles, estimated at about 100 μm . The quantity of the smaller particulates on the filter had not increased appreciably, if at all. A sizable quantity of wear debris had collected on the floor of the nozzle probably as the result of the relative confinement of the material compared with the earlier configuration of the collection chamber. At this time it was apparent that the tests were not producing airborne particulates in quantities that would permit collection

* The TIRF belt is made of stainless steel.

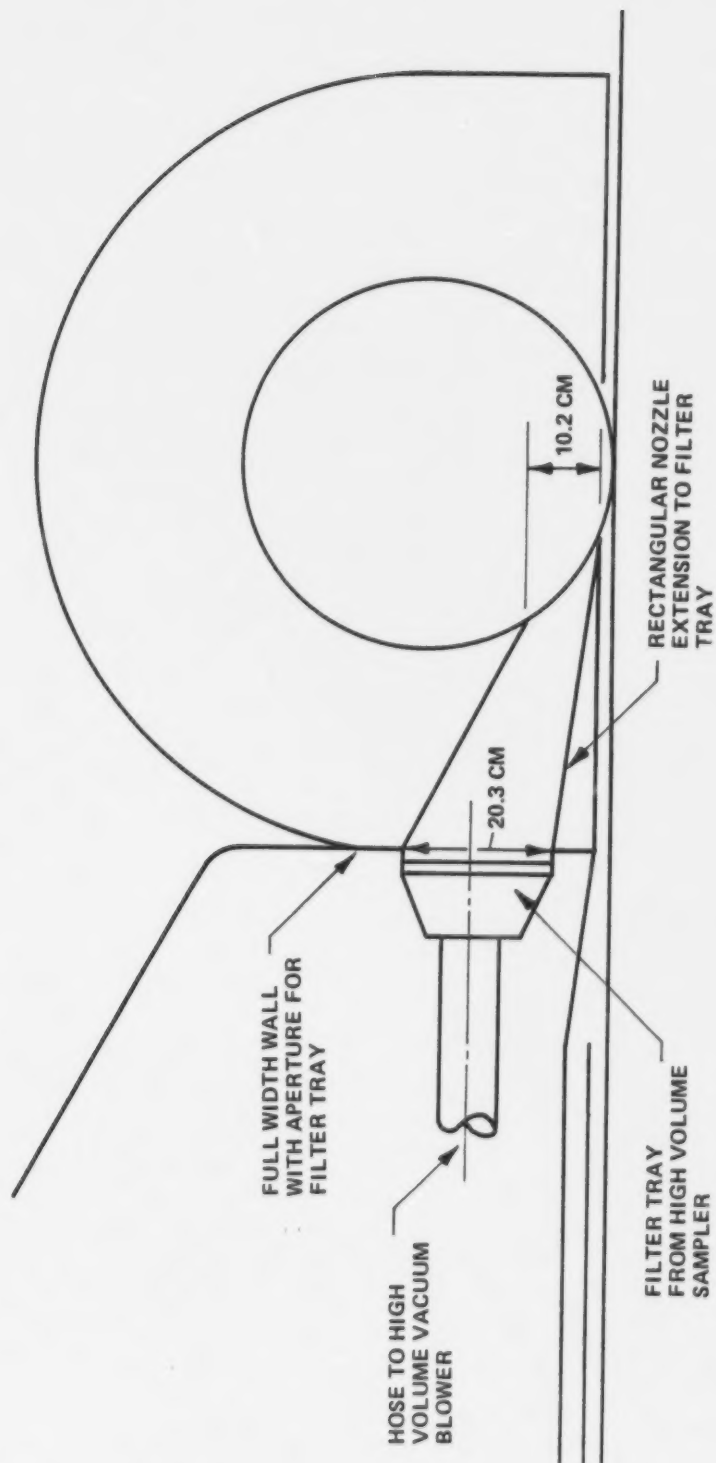


Figure 5 INTERNAL MODIFICATION TO PARTICLE COLLECTION CHAMBER AS USED FOR RUNS NO. 4, 5 AND 6 (PHASE A TESTS)

of a one-half gram sample within a reasonable test duration. The fundamental question was whether the absence of appreciable quantities (mass) of these particulates was a normal "real world" condition or an artifact of the type of tire tread wear that occurs on TIRF. More specifically, is the tacky tread surface of the tire the cause of (or the result of) small wear particles agglomerating to form larger-sized debris?

From experience with wear tests on TIRF (7) and other experimental data (16), it had been known that small quantities of "dust" introduced into the tire/roadway interface would result in tread surface textures that were smooth and nontacky. Cornstarch was found to be an acceptable dust. Cognizant of the adverse effect of the cornstarch on filter porosity, it was decided, nevertheless, to repeat run no. 4 using a small quantity of cornstarch.* During the one-half hour test, an estimated 0.11 kg (0.25 lb) of cornstarch was used in intermittent applications throughout the duration of the run. As expected, the high volume sampler filter paper became uniformly coated with cornstarch to a depth of about one to two millimeters. The cornstarch caught on the filters had a grayish, discolored appearance apparently caused by entrapped debris. Subsequent attempts to dissolve the cornstarch and filter the particulates were not successful. The most striking observation concerned the debris lying on the floors of the chamber. This debris appeared to be finely divided into individual small particles and was characterized by the complete absence of the large agglomerates observed on all previous runs. After only 30 minutes of operation the tire tread surface had assumed a smooth and nontacky texture.

Despite a convincing demonstration that dust inhibits the formation of large agglomerates, the question concerning the effect on the airborne fraction was not resolved.

As the final test run (no. 6) in this checkout series, wear particulates were collected with the tire operating in a cornering mode. Using the same enclosure configuration, instrumentation, load and torque as employed on runs no. 4 and 5, only the speed and slip angle conditions were changed. Speed was reduced to 40 km/h, and the slip angle was sinusoidally varied from $+3^\circ$ to -3° at a frequency of 0.1 Hz. A varying slip angle was employed to avoid severe asymmetrical wear of the tire since cornering represents a very high wear rate condition. After one-half hour of test, the filters were examined and found to have the same appearance as in all previous tests. The filters were weighed, and again no detectable change in weight could be observed. Very large quantities of rubber were deposited on the floor of the chamber. The debris tended to be in the form of ragged strands some of which were up to 15 cm in length. These strands were found to be very elastic and could undergo as much as 50% elongation before failing in tension.

* Mean particle size about 10 μm .

2. Discussion of Results

Upon completion of the Phase A checkout tests it was clear that a sufficient quantity of airborne particulates required for the EPA Ames tests would not be obtained if the planned test program (Table 1) were to be performed. Two factors were involved: (i) tests of one-half to one hour failed to generate a measurable weight of material, and (ii) such material as was collected was predominantly contaminant and not rubber. The cost of extending the test duration to the length necessary to collect the required weight of material would be prohibitive.

A continuing major concern has always involved the ability of indoor tests to duplicate the real world wear conditions of tires. The "real world" condition is really a catch phrase with no precise meaning because of the breadth of the ambient conditions involved. A brief reference to the published literature will support this contention. Tire wear mechanisms are qualitatively discussed in a survey article (11) which states that tread rubber characteristics and roadway characteristics interact to create deformation, adhesion and abrasion in the contact patch with both the micro- and macrostructure of the roadway surface playing an important role. Studies have shown that average tire tread life varies geographically over a range of almost four to one within the continental United States because of differences in highway surfaces and local topography (winding, hilly roads contribute to increased tread wear) (12). Road surface textures are also difficult to quantify.

Three basic mechanisms of tire wear have been identified; these are abrasive wear, fatigue wear and thermal decomposition of the rubber. Briefly, abrasive wear results from the cutting of tread rubber by sharp asperities and the removal of the rubber by sliding action in the contact patch. Fatigue wear is produced by a degradation of the tread rubber by mechanical fatigue. This type of wear frequently occurs under moderate wear conditions on smooth road surfaces. The tread surface appears to be liquid-like and smeared (13). Thermal mechanisms of tread wear are principally involved in locked-wheel braking conditions and spinning-wheel situations in acceleration. Temperatures produced in these circumstances may far exceed the decomposition temperature of the rubber.

Outdoor tests have been performed on specially-constructed tires to assess the effects of tread rubber compounds, road surfaces and driving conditions on the tread surface texture (13). It was determined that for tread rubber compounded of styrene-butadiene rubber (SBR), polybutadiene (BR), and mixtures thereof, all wear surfaces were similar for tests performed on very coarse (gravel) roads. On smooth concrete surfaces, the BR tread surface was found to be smooth with a fine granular texture. In contrast, SBR compounds were characterized by tread surfaces with "liquid-to-crumbled-appearing surface layers" thought to be caused by fatigue wear. Such tread surfaces have been reported to be sticky or tacky (13).

The foregoing discussion illustrates how elusive a simulation of real world tread wear conditions can be. It also shows that the sticky tread surface

condition that is frequently found when tires are operated on steel drums, rolls or coated steel belts (TIRF) is not unique to the laboratory environment.

The most promising method that could be readily implemented in changing the type of tread wear produced in TIRF was that of modifying the roadway surface characteristics. To avoid the tacky tread surfaces associated with roadway surfaces characterized by a fine microstructure, it is necessary to introduce a macrostructure as well. To this end, a conformable-type of Safety-Walk* material was obtained and applied over a very coarse open-coat abrasive comprised of large, blocky grits. The result of this laminated combination was a surface that combined a micro- and macrostructure that resembled asphalt.

To test the durability of this laminated roadway covering and to determine the type of tire tread surface that would be produced by a tire operating upon it, some simple tests were made on a 1.2 m (4 ft) drum. A bias tire was operated under load on this drum whose test surface was covered with the laminated coating. After several hours of operation at 80 km/h, the tire surface appeared slightly abraded, nontacky and free of any buildup of rubber. The conformable Safety-Walk appeared to be intact. Based on this encouraging result, a revised test schedule was formulated and forwarded to the project officer for approval. The next section discusses the details of the Phase B test effort.

C. Tire Wear Tests, Phase B

1. Test Plan Details and Rationale

The Phase B test plan differed in two major respects from the initial schedule as summarized in Table 1; namely, the tire wear schedule and the roadway surface characteristics.

Previous studies concerned with tread wear of passenger car tires on the TIRF machine (7) had resulted in the development of tire wear schedules that produced controlled wear rates combined with a uniform wear across the tire tread surface. Using cornstarch (not practical in the current program), the worn tire surfaces were judged to be very representative of "road worn" tires. The test conditions selected on this basis are listed below.

- pressure: 165 kPa (24 psi) cold, capped
- vertical load: 3985N (896 lb)
- roadway speed: 88 km/h (55 mph)
- slip angle:
 - 0.3° rms, random (Gaussian) amplitude distribution
 - period of randomness: 22.7 minutes

* This 3-M product is made in the same surface texture grades as regular Safety-Walk but uses an aluminum foil backing treated with contact cement.

camber angle: 0°

wheel torque:

- ±68 N-m (±50 ft-lb) sinusoidally varying
- frequency of input = 0.1 Hz

test duration: three hours

Both the bias and the radial tire were to be subjected to the same test schedule which was estimated to produce wear rates of about 0.025 mm/km (16 mils/1000 miles) for the former and 0.016 mm/km (10 mils/1000 miles) for the latter. Tires previously unused under test conditions, but broken-in, were employed for these tests.

Despite the promising test results obtained with the use of the laminated roadway surface covering (a conformable Safety-Walk overlay on a coarse, abrasive paper) on the drum, the feasibility of its use on the TIRF machine remained uncertain. In the TIRF application these materials would be subjected to repetitive flexing and sizable longitudinal/lateral forces that did not exist during the drum tests. Also, the conformable material uses a contact cement as the adhesive. If the surface integrity of the Safety-Walk were to be compromised during testing, the collected sample of debris would be contaminated with this adhesive which contains known carcinogens. The purpose of the test would then be nullified. Nevertheless, the decision was made to conduct tests on the laminated roadway surface material with the backup option of reverting to the standard Safety-Walk if necessary.

For these tests the test chamber was returned to its normal configuration as shown in Figure 4. It was thoroughly cleaned and reinstalled on the TIRF machine. The TIRF roadway was partially covered* with the experimental, laminated surface.

The first test run was performed on the radial tire. After three hours of test, the filters from the high volume samplers were generously covered with debris. Debris that had settled to the floor of the chamber was in the shape of small granular particles. Tire tread surfaces appeared slightly abraded but tactilely smooth and nontacky. A slight accretion of rubber was observed on one of the outer ribs of the tread.

This run was considered to be a checkout test of the roadway surface. While the composition of the airborne sample was being analyzed with the SEM, a second test run was started. A portion of the conformable Safety-Walk surface separated from the TIRF belt after approximately 15 minutes. In the effort to improve adhesion, a length of conformable Safety-Walk extending the full width of the steel belt was applied over the 30 cm strip of abrasive underlayer. The adhesion problem was not resolved by this expedient. Also, the analysis of the particulates showed that the airborne fraction consisted mainly of stainless steel, aluminum, silicon and contact cement. Clearly, the roadway surface was being degraded by the loss of entire grits together with the foil backing and the cement. Samples thus were unacceptably contaminated. Consequently, it was necessary

* A continuous, circumferential strip, 30 cm wide, was centrally placed on the 71 cm wide TIRF belt.

to return to the standard Safety-Walk material to generate the particulate samples to be used in the EPA bioassay. Nevertheless, caution must be exercised in the interpretation of mutagenicity test data due to the possible contamination of the rubber samples by the adhesive used with standard Safety-Walk as well.

After the collection chamber had been thoroughly cleaned again and the TIRF belt resurfaced with standard Safety-Walk, three tests of three hours duration each were performed; one on the bias tire and two on the radial tire.

2. Test Results

This section summarizes the results of analyses performed on tire wear particulates collected during the final three test runs made on this program; runs no. 7, 8, 9. Runs no. 7 and 8 were made on the DR78-14 and D78-14 tires, respectively. Since the total mass of particulates deposited on the floor of the enclosure during run no. 7 was judged to be marginal, run no. 9 was made on the same radial tire as a repeat of run no. 7 to collect additional particulates for the bioassay study. The presentation of the data is divided into two parts; the first part being devoted to analysis of the nonairborne particulate samples which deposited on the flat, horizontal surfaces (floors) of the chamber and the second part concerned with the airborne particulate samples collected by the high volume samplers and the cascade impactor. Separate treatment is accorded to the samples from the radial and the bias tires.

a. Analysis of the Settled Particulates - (Floor Samples)

Measurements were made of the particle sizes and their frequency of occurrence for the wear debris which had settled on the filter paper* lining the floor of the main settling chamber. Representative filter sections were physically removed from the sheet of filter paper for analyses. Photographs of the samples were taken with the aid of an optical microscope at various levels of magnification to accommodate particulates in the size range below about 300 μm . The eyepiece of the microscope was fitted with a graduated reticle to permit measurement of particle sizes. Particulate shapes were observed to be very irregular and characterized by a structure that appeared to be very porous (sponge-like). Subsequent analysis identified all these larger-sized particles as consisting essentially of rubber. Particle sizes were quantitatively measured from photomicrographs of the samples, with the size being given in terms of the long dimension of the particle. For each of the three test runs, several hundred particles were sized in this manner to assure reasonable statistics of counting. The results were then presented in terms of the percentage of the total particle count that was found within a given particle size range. The size range to 80 μm was divided into fractions, each with a width of 10 μm . The size range

* Pallflex fiberglass filter paper (No. T60A20), a teflon-coated paper, was also used in the high volume samplers.

from 80 μm to 300 μm encompassed 11 fractions, each with a width of 20 μm . Using the midpoint-size value of each fraction as the ordinate, the data are summarized in Figure 6 as plots on probability paper where the abscissa is cumulative probability.

The two runs on the same radial tire show slightly different distributions which probably are the result of the modest numbers of particles constituting these sized samples. An alternative possibility is that rubber buildup on the tread surface with mileage resulted in larger particulates being produced during the second run (run no. 9) on the radial tire. A bimodal distribution is found for both samples with a sharp transition occurring at a particle size of 50 μm . Median particle sizes for these two distributions lie in the approximate range of 25 μm to 35 μm . A different distribution was observed for the wear particulates produced by the bias tire. The distribution is curvilinear, in contrast to the straight-line segments that characterize the distribution data for the radial tire. Also the bias tire is found to produce larger particles with the median size at about 55 μm . Median particle sizes shown in Figure 6 compare favorably with values of 20 μm to 30 μm reported for test samples collected behind a tire on a vehicle operating in a normal mode on a concrete highway (3). When the collection system was redesigned to improve the collection efficiency for the smaller particles, the median size values dropped to the 10 μm to 15 μm range (3).

In the TIRF tests, the enclosure is designed to separate the smaller particles by keeping them airborne and hence capable of capture by the high volume samplers and the cascade impactor. Thus, the floor sample will be deficient in these smaller particles, and the data of Figure 6 must be viewed as applicable only to the floor sample of wear particulates and the specific circumstances and constraints attendant to their collection. Nevertheless, the agreement between TIRF data and the data from reference 3 (with the inefficient collection of small particles) strongly indicates that wear particulate size distributions produced on TIRF are not unlike those produced during normal vehicle operation on highways. It also follows that the bimodal distribution observed for the radial tire may be an artifact of the effect of the test environment on the collection of the sample.

Using the same sections of filter paper employed for the particle-size measurements discussed above, an analysis of a representative sample of the particles was made for composition using scanning electron microscope (SEM) techniques. A description and validation of these techniques is presented in Appendix B. Basically, the elements comprising the particle(s) are identified by their characteristic x-ray spectra. Since hydrocarbons cannot be identified by this method, rubber is detected by the simultaneous appearance of energy peaks corresponding to sulfur (S) and zinc (Zn) which are constituents of tread rubber compounds. Table 2 lists the size (length by width or diameter) of 50 randomly selected particles together with the elemental composition of each particle from the floor sample generated by the radial tire. Of the 50 particles examined, 92% were rubber with 65% of these also containing other debris. Of the contaminated particulates 41% contained iron (probably stainless steel).

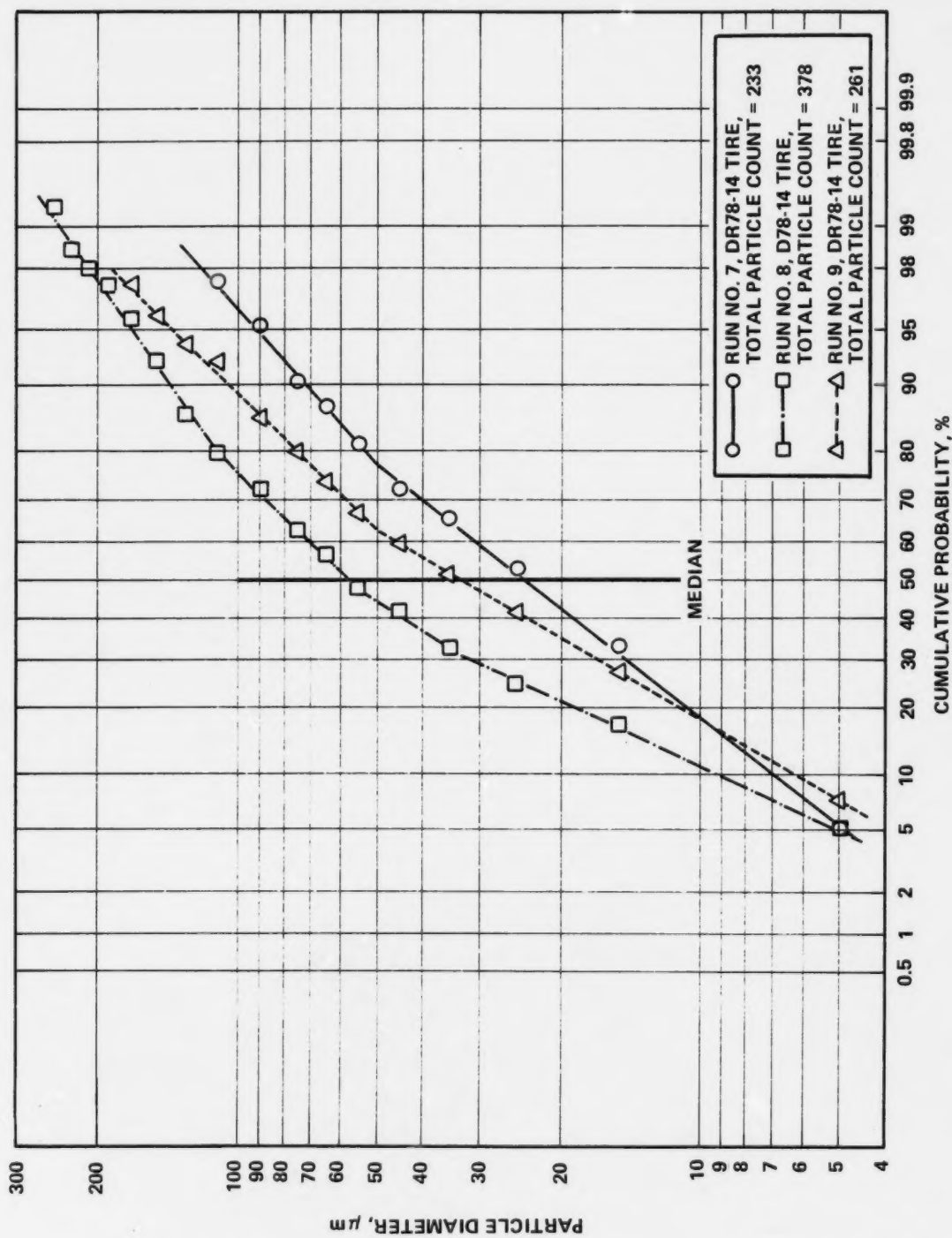


Figure 6 PARTICLE SIZE DISTRIBUTION OF SAMPLES FROM THE FLOOR OF THE COLLECTION CHAMBER
(Approximately 90% of these Particles Contained Rubber)

TABLE 2

Size and Elemental Composition of 50 Tire Wear Particulates;
Floor Sample Run No. 7, Radial Tire (DR78-14)

Particle No.	Particle Size L x W (μm)	Particle Identification: (Elemental Composition)										Particle Identification: (Elemental Composition)									
		Particle Identification: (Elemental Composition)										Particle Identification: (Elemental Composition)									
		Rubber	Fe	Ca	K	Cl	Al	Mg	Na	Other	Rubber	Fe	Ca	K	Cl	Al	Mg	Na	Other		
1	30 x 40	x																			
2	30 x 100	x																			
3	15 x 40	x																			
4	40 x 80	x																			
5	30 x 40	x																			
6	20 x 80	x																			
7	40 x 80	x																			
8	30 x 50	x																			
9	15 x 30	x																			
10	30 x 150	x																			
11	15 x 20	x																			
12	25 x 50	x																			
13	8 x 30	x																			
14	8 x 110	x																			
15	40 x 120	x																			
16	100 x 130	x																			
17	100 x 150	x																			
18	30 x 70	x																			
19	50 x 60	x																			
20	100 x 150	x																			
21	50 Dia.	x																			
22	120 x 180	x																			
23	15 x 20	x																			
24	220 x 250	x																			
25	100 x 150	x																			

Fe = Iron, Ca = Calcium

K = Potassium Cl = Chlorine

Al = Aluminum Mg = Magnesium

Na = Sodium

Fe = Iron,
Ca = Calcium

K = Potassium
Cl = Chlorine

Al = Aluminum
Mg = Magnesium

Na = Sodium

Table 3 shows similar data for 50 particles examined from the floor sample generated by the bias tire. Here 90% of the particles were rubber with 24% of these containing contaminants. Iron appears less frequently as a rubber contaminant (~9%) than in the case of the radial tire sample. In both samples, tire particulates appear to be blocky or chunky in shape rather than elongated. For example, $\approx 75\%$ of the particles generated by the radial tire and $\approx 60\%$ of those by the bias tire, have a length-to-width ratio of <2.5 . A few spherical particles were also detected. Differences in particle morphology are illustrated in Figures 7 and 8.

Figure 7a is a photograph of an irregularly shaped rubber particle, approximately 95 μm in length,* that appears to be an agglomerate. Figure 7b is an annotated x-ray spectrum of the particle showing energy peaks corresponding to S, Zn, silicon (Si), copper (Cu), gold (Au), and palladium (Pd). The last two elements originate from the conductive coating that must be applied to electrically nonconducting specimens (see Appendix B). Figures 8a and 8b illustrate smooth-surfaced, spherically-shaped rubber particles with diameters of $\approx 15 \mu\text{m}$ and $\approx 50 \mu\text{m}$ respectively.

b. Analysis of the Airborne Particulates

Airborne particulates, in the context of this section, denote particulates that were collected by the high volume samplers as well as by the cascade impactor. In analyzing the particulates from the hi-vol units, the choice was made to use the samples from the hi-vol located in the secondary chamber since it collected a larger range of particle sizes, by virtue of chamber design, than the unit operating in the main chamber. A gross field (30X) SEM photograph is shown in Figure 9a to illustrate the nature of the particulates collected by the hi-vol samplers during the tests on the radial tire. The x-ray spectrum obtained from a scan of the field of Figure 9a is shown in Figure 9b where the various identifiable elements present are noted. Portions of this field are shown at magnifications of 300X and 3000X (Figures 10a and 10b, respectively) to better define the nature of the particles in the $\approx 1 \mu\text{m}$ size range. The fibrous structure of the fiberglass filter paper is clearly a limiting factor in locating and analyzing particles in the submicron size range. Results of an analysis of the individual particulates are summarized in Table 4. The larger particulates, individually identified by a number that locates each on either Figure 9a or 10a, are listed in Table 4A and are seen to be principally rubber particles. Table 4B lists the elemental composition of the smaller particles that are identified by size only. These particles are seen to consist chiefly of contaminants with only a few rubber particles identified.

Rubber particles, in the main, are seen to be coarse, irregular and sponge-like. They are neither smooth nor cigar-shaped and thus appear to be abraded from the tire by a scraping action.

* All SEM photographs in this report have a size scale (a horizontal line terminated by two short vertical bars) at the bottom margin. To the left of this scale is the numerical value, in micrometers, of the line length.

TABLE 3

Size and Elemental Composition of 50 Tire Wear Particulates;
Floor Sample, Run No. 8, Bias Tire (D78-14)

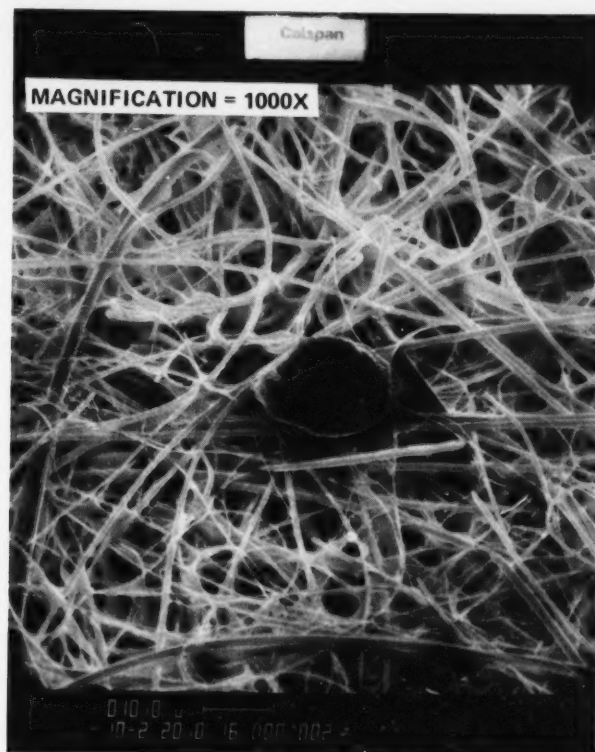
Particle No.	Particle Size L x W (μm)	Particle Identification: (Elemental Composition)										Particle Identification: (Elemental Composition)									
		Rubber	Zn	Fe	Ca	K	Cl	Al	Na	Other	Rubber	Zn	Fe	Ca	K	Cl	Al	Na	Other		
1	120 x 120	x																			
2	40 x 90	x																			
3	10 x 20	x																			
4	150 x 250	x																			
5	20 x 100																				
6	50 x 120	x																			
7	150 x 300	x																			
8	10 x 12																				
9	100 x 150	x																			
10	200 x 400	x																			
11	20 x 100	x																			
12	50 x 150	x																			
13	30 x 55	x																			
14	25 x 40	x																			
15	150 x 300	x																			
16	30 x 80	x																			
17	20 x 50	x																			
18	30 x 50	x																			
19	80 x 200	x																			
20	40 x 50	x																			
21	30 x 45	x																			
22	12 x 20	x																			
23	200 x 300	x																			
24	20 x 100	x																			
25	100 x 500	x																			

Fe = Iron
Ca = Calcium

K = Potassium
Cl = Chlorine

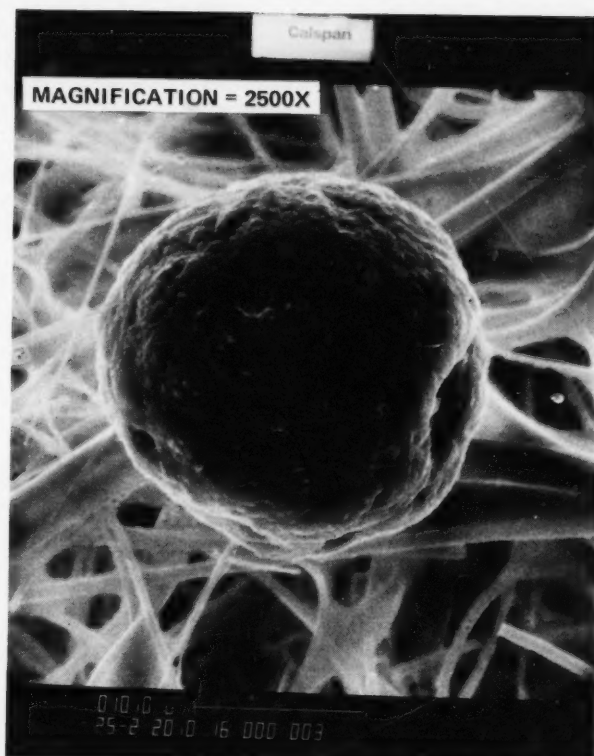
Al = Aluminum
Zn = Zinc

Na = Sodium



MAGNIFICATION = 1000X

(a)



MAGNIFICATION = 2500X

(b)

Figure 8 SEM PHOTOGRAPHS OF TWO SPHERICALLY-SHAPED RUBBER PARTICLES FROM THE FLOOR SAMPLE OF RUN NO. 8, D78-14 BIAS TIRE

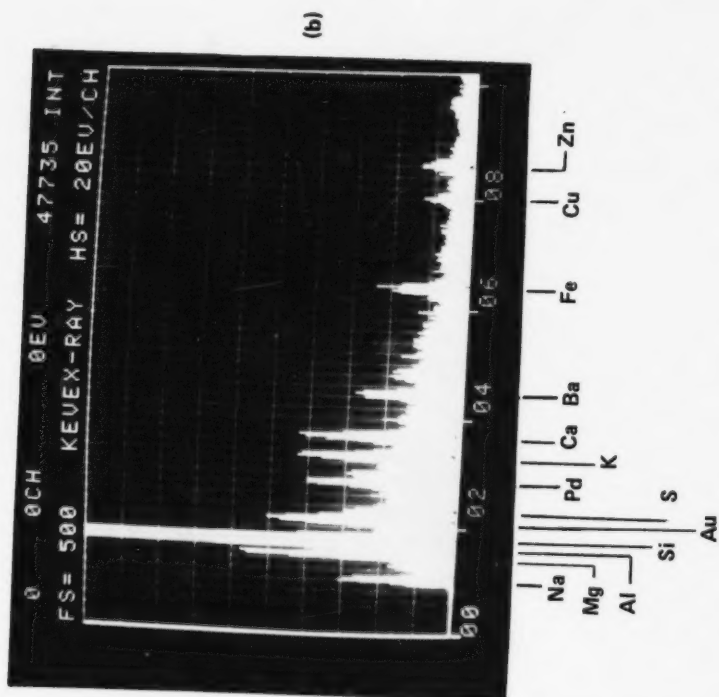
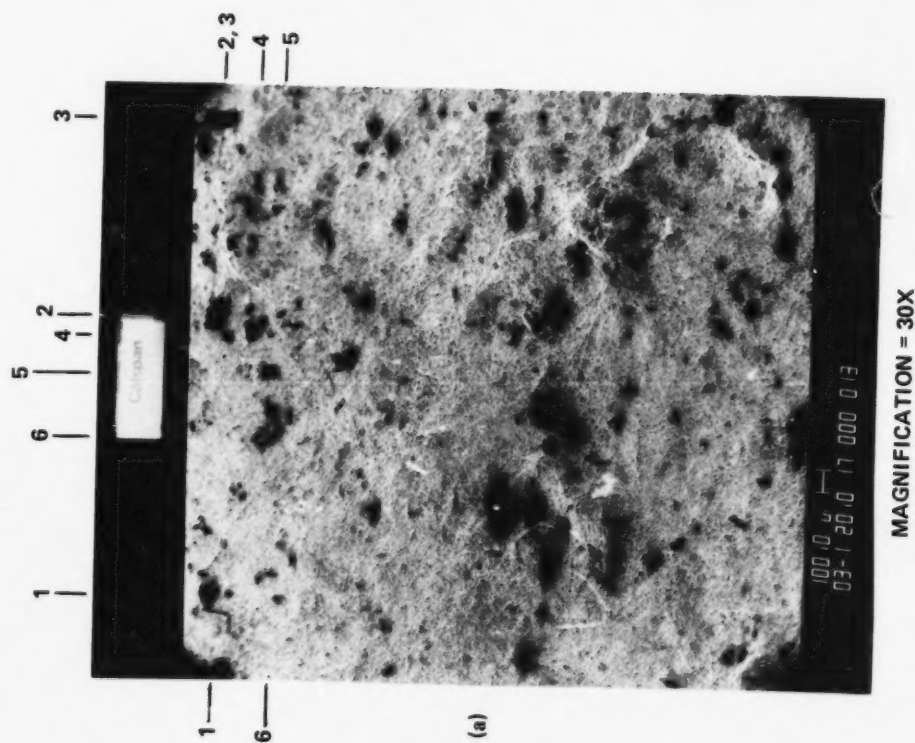


Figure 9 SEM FIELD-VIEW PHOTOGRAPH OF HI-VOL FILTER SAMPLE AND ANNOTATED, COMPOSITE X-RAY SPECTRUM; RADIAL TIRE (DR78-14)

Particle No.	Rubber	Si	Organic; No Spect-rum	SEM Photo Magnif.
1	x			30X (Fig.9a)
2	x			
3	x			
4	x			
5	x			
6	x			
7			x	300X (Fig.10a)
8	x			
9	x			
10	x			
11		x		

(A)

Particle I.D. by Size, μ m	Rubber	Zn	Ca	Fe	Cl	Si	Al	Mg	Stain-less	No Spect-rum	SEM Photo Magnif.
15 x 20	x										3000X (Fig.10b)
3 x 8			x								
$\sim$ /dia.				x							
4 x 5				x							
20 x 30	x										
25 x 30	x										
5 x 30										x	
4 x 6		x									
5 x 7				x							
2 x 3										x	
2 x 5						x		x			
20 x 30				x							
10 x 12					x						
2 x 3				x							
4 x 5									x		
4 x 5							x				

(B)

TABLE 4

Elemental Composition of Particles From the Hi-Vol Filter Sample, Radial Tire (DR78-14) (Ref. Figures 9a, 10a and 10b)

An analysis identical to that described above for the radial tire, was performed for the hi-vol sample obtained for test run no. 8 performed on the bias tire. The data are shown in Figures 11, 12 and Table 5 which are counterparts to Figures 9, 10 and Table 4, respectively. In general, the same observations and comments apply to both sets of data. Table 5 shows, as did Table 4, that the larger particles are primarily rubber (or rubber plus contaminants) while the smaller particulates are mostly contaminants. In fact, none of the small particles examined in Figure 12b contained any rubber.

A six-stage Battelle cascade impactor sampled particulates from within the main collection chamber while operating at a volumetric flow rate of 12.5 liters per minute. Instrument specifications are tabulated below:

<u>Stage No.</u>	<u>Particle Mean Cut-off Diameter, μm</u>
1	16
2	8
3	4
4	2
5	1
6	0.5

with the mean cut-off diameter defined for spherical particles of unit density* wherein 50% will impact a given stage and 50% will continue to a succeeding stage. Millipore Fluoropore filters (teflon) were used to collect the particulates on each of the six impactor stages.

A representative collection of particulates collected on the 4th stage filter during run no. 9 on the radial tire is shown in Figure 13a. The particles are in the approximate 1 μm to 7 μm range, and, as indicated by the composite x-ray spectrum of Figure 13b, consist chiefly of contaminants. Table 6 summarizes the composition of 18 specific particles that are identified (by number) on Figure 13a. The overwhelming majority of the particles contain stainless steel.**

Figure 14a presents a collection of particles from the 5th stage of the impactor in run no. 8 (the bias tire). Figure 14b is the composite x-ray spectrum of the field shown in Figure 14a. Particle sizes are in the 1 μm to 3 μm range and again contain no identifiable rubber particles. Of 17 particles analyzed for elemental content (see Figure 14a and Table 7) it is seen that all but one contained stainless steel.

* Tread rubber density is about 1.18 (3).

** Particles whose x-ray spectra showed both iron and chromium peaks were classified as stainless steel.

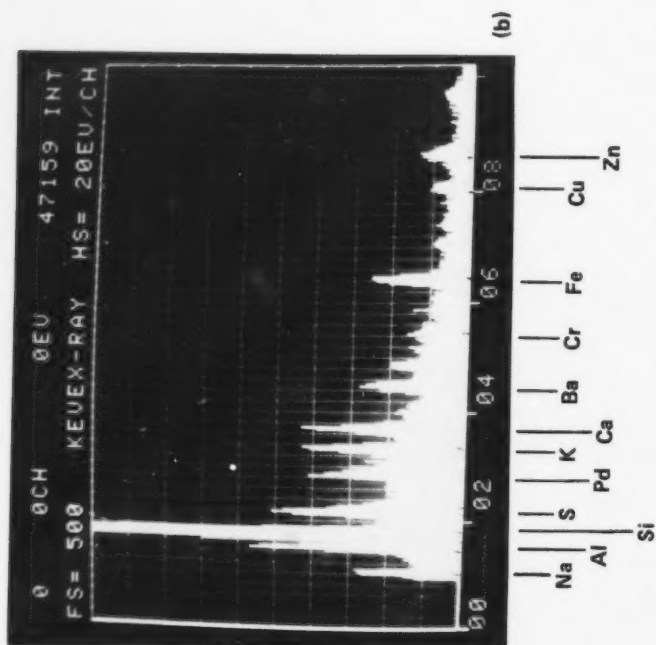


Figure 11 SEM FIELD-VIEW PHOTOGRAPH OF HI-VOL FILTER SAMPLE AND ANNOTATED, COMPOSITE X-RAY SPECTRUM; BIAS TIRE (D78-14)

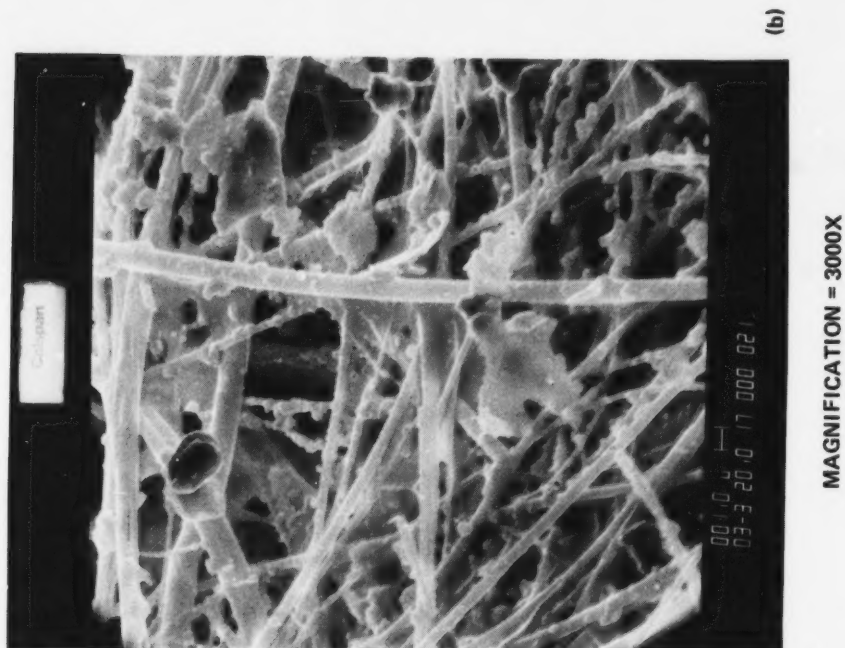
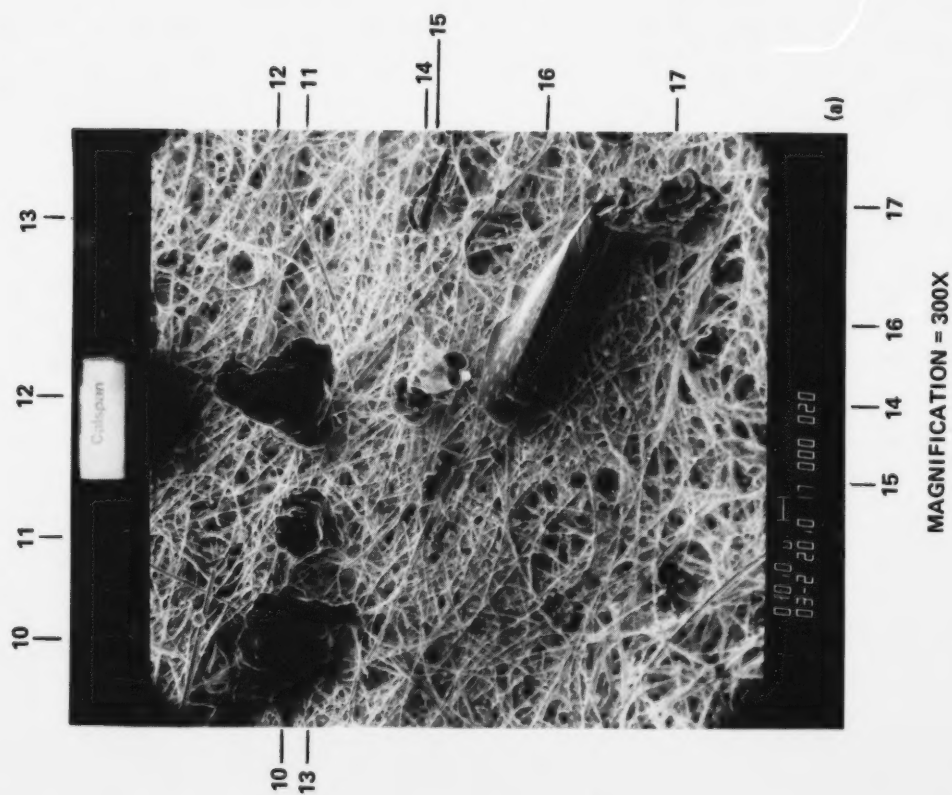


Figure 12 SEM PHOTOGRAPHS OF HI-VOL FILTER SAMPLE AT HIGH MAGNIFICATIONS;
BIAS TIRE (D78-14)

Particle No.	Rubber	Ca	Fe	Ti	Si	Al	Organic, No Spectrum	Other	SEM Photo Magnif.
1	x								30X (Fig.11a)
2	x		x						
3	x								
4					x				
5	x								
6	x	x	x	x					
7	x								
8	x								
9	x		x						
10	x	x				x			
11							x		300X (Fig.12a)
12	x	x	x						
13							x		
14	x								
15	x								
16					x				
17	x								

(A)

Particle I.D. by Size, μ m	Rubber	Fe	Zn	Al/Si	Gyp-sum	Stain-less	SEM Photo Magnif.
2 x 3		x					3000X (Fig.12b)
3 x 5			x				
3 x 5			x				
4 x 8				x			
4 x 5					x		
2 x 3						x	
3 x 5						x	
8 x 15						x	
4 x 5			x				

(B)

TABLE 5

Elemental Composition of Particles From the Hi-Vol Filter Sample, Bias Tire (D78-14), (Ref. Figures 11a, 12a and 12b)

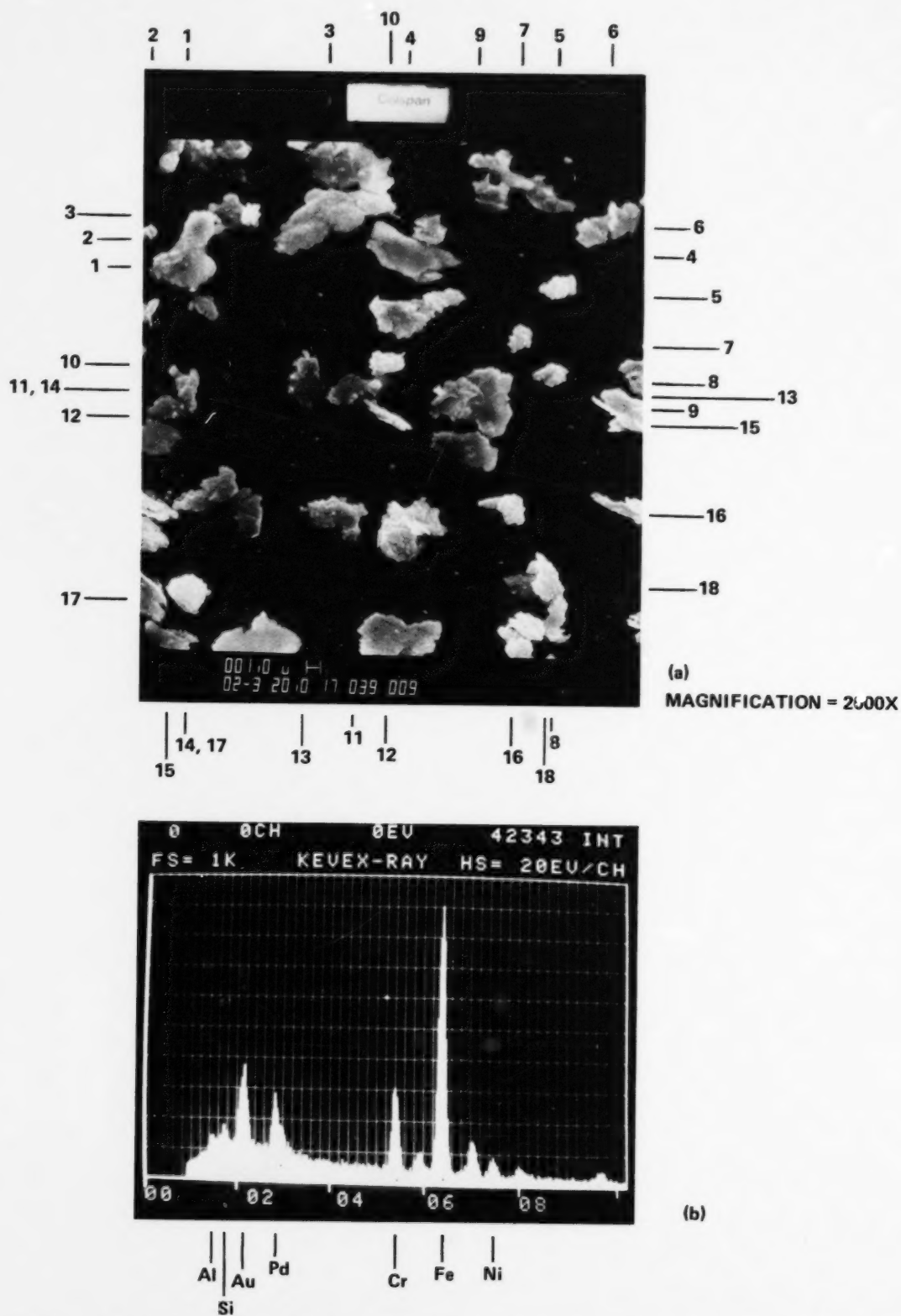


Figure 13 SEM FIELD VIEW PHOTOGRAPH OF CASCADE IMPACTOR FILTER SAMPLE (STAGE 4) AND COMPOSITE ANNOTATED X-RAY SPECTRUM; RADIAL TIRE (DR78-14), RUN NO. 9

Particle Number	Rubber	Fe	Ca	Cl	S	Si	Al	Mg	Na	Stainless Steel	Other
1										x	
2			x		x	x	x	x			
3		x									
4										x	
5										x	
6						x					
7										x	
8										x	
9						x				x	
10				x		x	x			x	x
11					x	x	x			x	
12										x	
13										x	
14						x	x			x	
15		x	x		x	x	x				
16		x	x	x	x	x	x	x			
17						x	x	x	x	x	
18						x	x			x	x

TABLE 6

Elemental Composition of Particles From Stage 4
of the Cascade Impactor;
Radial Tire (DR78-14), Run No. 9 (Ref. Fig. 13)

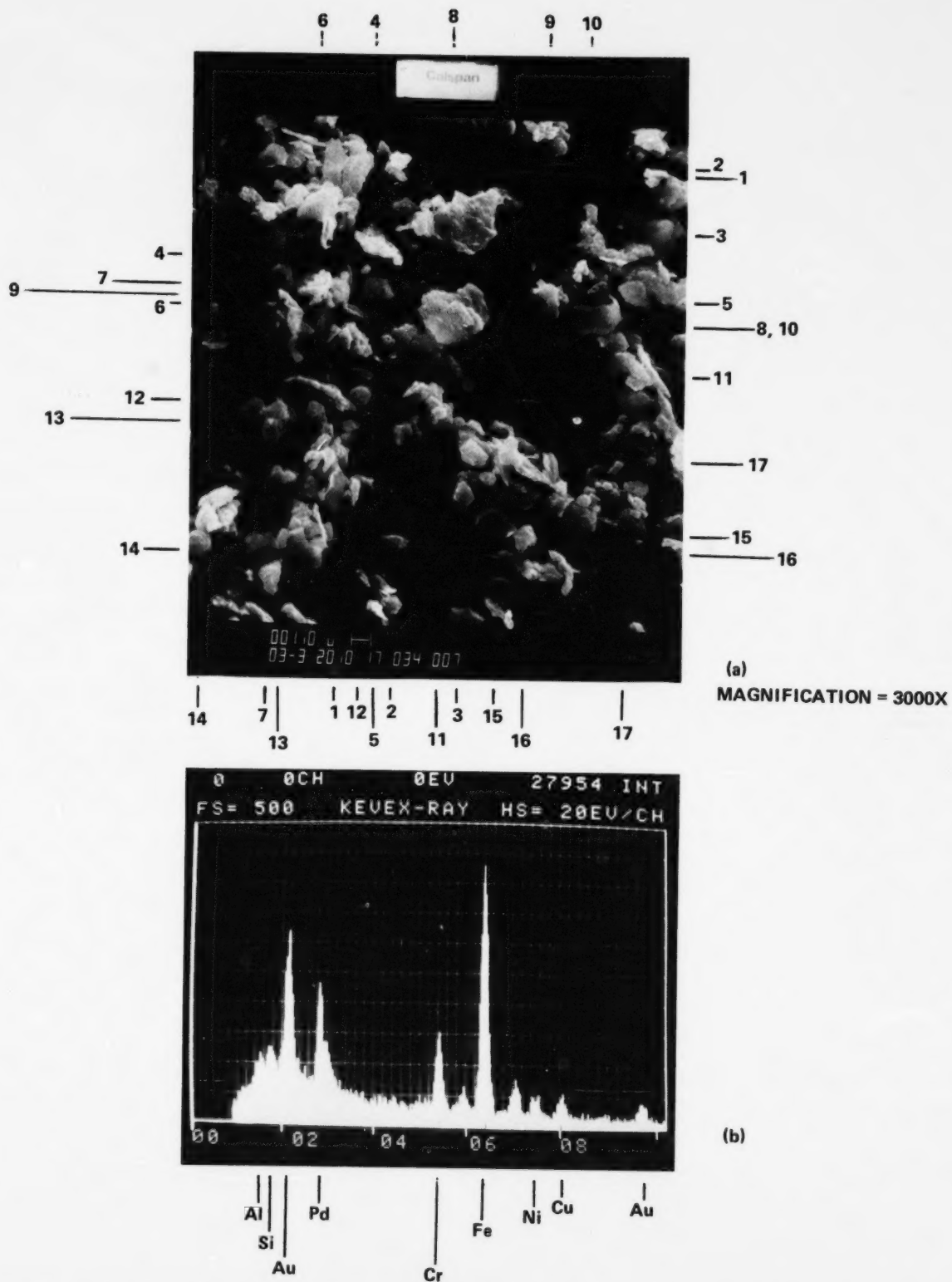


Figure 14 SEM FIELD VIEW PHOTOGRAPH OF CASCADE IMPACTOR FILTER SAMPLE (STAGE 5) AND COMPOSITE ANNOTATED X-RAY SPECTRUM; BIAS TIRE (D78-14), RUN NO. 8

Particle Number	Rubber	Zn	Cu	Fe	Ca	Cl	S	Si	Al	Na	Stain- less Steel
1											
2											x
3				x				x	x		x
4											
5											x
6								x	x		x
7											x
8											x
9		x	x			x		x	x		x
10											x
11											x
12					x	x	x	x	x	x	x
13											x
14							x	x			x
15											x
16								x	x		x
17											x

TABLE 7

Elemental Composition of Particles from Stage 5
of the Cascade Impactor;
Bias Tire (D78-14), Run No. 8 (Ref. Fig. 14)

A careful examination of the high magnification SEM photographs of the impactor samples, see Figure 13a and 14a for example, shows a considerable number of tiny, regularly-shaped particles. To ascertain the nature of such particles, the 6th stage sample was analyzed from a run on the bias tire. Figure 15a depicts a sampling of particles in a size range $\leq 1 \mu\text{m}$. The x-ray spectrum (Figure 15b) of three identified particles shows the presence of sulfur and zinc peaks which classify these particles as rubber. Figure 16 consists of high-magnification (20,000X) photographs of the three particulates which show smooth, regular shapes in contrast to the morphology of the larger particulates. These results indicate an absence of rubber particles in the approximate size range from $1 \mu\text{m}$ to $10 \mu\text{m}$ but their presence on either side of this size interval. This finding is in agreement with results reported by General Motors on particle emissions from tires (1) but conflicts with the work of Pierson at Ford (2).

Filters installed in the two hi-vol samplers and the Battelle impactor were weighed before and after a test run in the attempt to determine the weight of the collected particulates. A summary of the results obtained is presented in Table 8. Approximately four times the mass of particulates was collected on the hi-vol filters for the radial tire as for the bias tire. Thus, a lesser portion of the wear particulates generated by the bias tire was airborne than for the radial tire.

The weight data for the filters from the Battelle impactor are considered to be within the noise level of the measurement capability. For example, one of the filters was measured as having decreased on weight by 0.4 mg after a test run. It is clear that considerably longer duration test times would be required to collect accurately measurable weights of particulates on the impactor stages. Due to an oversight created by illness to key technical personnel during these final tests, measurements of the total weight of rubber removed for each run were not made, and hence data on the wear rates applicable to these runs are not available.

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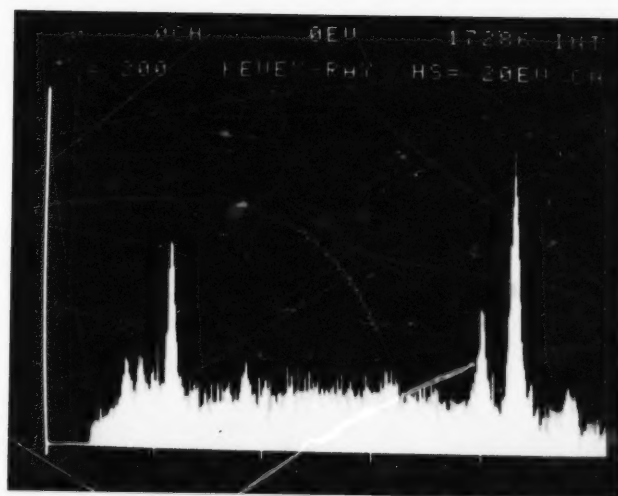


— 3
— 1
— 2

(a)

MAGNIFICATION = 2000X

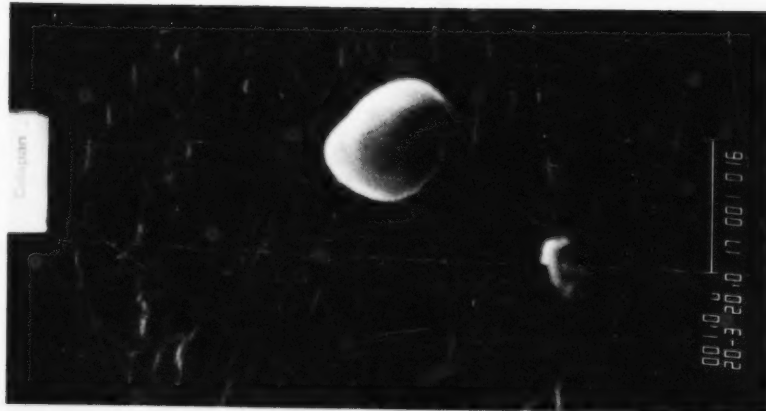
1 2 3



(b)

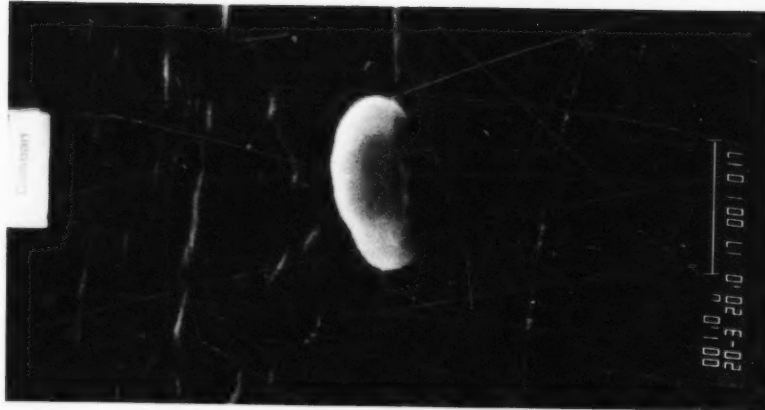
Figure 15 SEM FIELD VIEW PHOTOGRAPH OF CASCADE IMPACTOR FILTER SAMPLE (STAGE 6)
AND ANNOTATED X-RAY SPECTRUM FOR THE THREE IDENTIFIED PARTICLES

PARTICLE 1



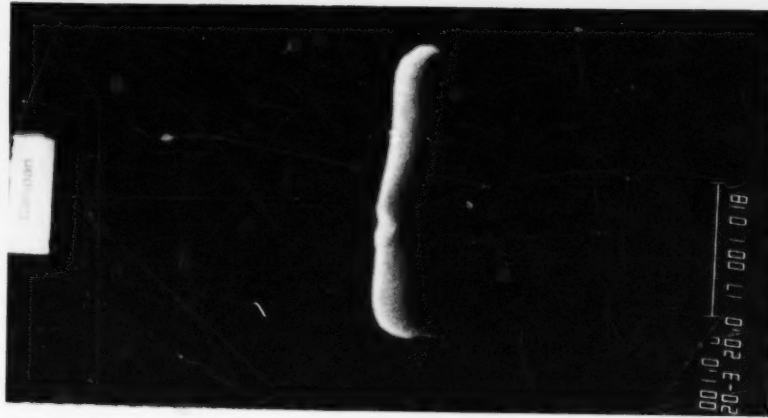
MAGNIFICATION = 20,000X

PARTICLE 2



MAGNIFICATION = 20,000X

PARTICLE 3



MAGNIFICATION = 20,000X

Figure 16 SEM HIGH-MAGNIFICATION PHOTOGRAPHS OF THREE PARTICLES FROM STAGE 6 OF THE CASCADE IMPACTOR; BIAS TIRE PARTICULATES

TABLE 8

Weights of Tire Wear Particulates Collected During the Phase B Tests

Run No.	Tire	Test Details	Hi-Vol. No. 1 Δm , g	Hi-Vol. No. 2 Δm , g	Battelle Impactor Stage No.	Δm [†] , g
7	DR78-14 (Tire No. 3)	Velocity: 88 km/h Load: 3985N Slip Angle: * Camber: 0° Torque: ** Pressure: 165 kPa (cap) Duration: 3 hours	0.32	0.14	1 2 3 4 5 6	0.0010 0.0006 0.0009 0.0005 0.0011 0.0009
8	DR78-14 (Tire No. 2)	Same as Run 7	0.04	0.08	1 2 3 4 5 6	0.0008 0.0009 0 0.0002 0.0002 0.0006
9	DR78-14 (Tire No. 3)	Same as Run 7	0.26	0.22	1 2 3 4 5 6	-0.0004 0.0003 0 0.0005 0.0006 0.0001

Note: Weights of particulates shown above do not represent total wear. Wear rates were not determined for these tests.

*0.3° RMS With a Gaussian Amplitude Distribution

**168N-m Sinusoidally Varying, Frequency = 0.1 Hz

† Δm = Difference in Post Test and Pretest Weight of Filter

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* Related reference material:

- a) W. R. Pierson and W. W. Brachaczek. In-Traffic Measurements of Airborne Tire-Wear Particulate Debris, JAPCA 25, 404-405 (1975).
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APPENDIX A

AN ESTIMATE OF TRUCK TIRE WEAR PARTICULATE CHARACTERISTICS

The purpose of this appendix is to attempt to determine the expected characteristics of tire wear particulates from truck tires. Extrapolation from measurements made on passenger car tires is to be made on the basis of engineering judgment taking into account differences in tire sizes, construction and tread formulations as well as the differences in usage patterns of automobiles and trucks. Since this effort must include the entire spectrum of trucks, the results of this analysis must perforce be broadly drawn and exceedingly general.

Truck tires are characterized by a broad range both in physical size and construction as well as in operation. This stands in direct contrast with passenger car tires which are designed to operate over very limited ranges of both inflation pressure and load. Tires on passenger cars operate at loads which range over narrow limits while truck tires are subject to very wide ranges of loads corresponding to that of an unloaded vehicle to one that is loaded to its maximum gross vehicle weight rating. Table A-1 illustrates the physical differences in size and ratings for a selected sampling of passenger car and truck tires. Note that the passenger car tires are limited to a maximum inflation pressure of 32 psi while truck tires are only limited by the rating of the rims on which they are used.

Data on the usage of trucks is relatively limited and often atypical of national averages. The following information has been obtained from references 14 and 15. The majority of motor trucks are used in the immediate proximity of the home base of operations. Typically only 2% of all trucks regularly travel more than 200 miles from the point of origin of the trip. Nearly 73% of all light truck movements are local as contrasted with 50% for heavy units. In this study, light trucks were defined to include 2-axle, 4-tire vehicles with payload capacities of one-half to one and one-half tons and a GVW less than 10,000 lbs. The principal findings are that the usage of motor trucks, like usage of passenger cars, tends to concentrate in urban areas. There is a clear difference, however, in usage between light trucks and heavy trucks (GVW > 10,000 lbs). Light trucks are predominantly urban oriented. Based on statistics obtained by pooling survey data from 11 urban areas, the light truck accounted for 72% of all truck trips (on an average daily usage basis), 65% of all truck miles and 96% of all trucks employed for personal use. Of the total daily one-way trips made by light trucks, 27% were without load. The light truck was found to average 28 miles and 5.9 trips per day. The medium heavy trucks (GVW > 10,000 lbs) account for 35% of the daily truck miles with a per vehicle mileage of 36.5 miles and an average trip length of 3.8 miles. Table A-2 is a summary of the numerical data.

TABLE A-1

Comparison of Selected Specifications and Ratings for a Sample of Typical Automobile and Truck Tires

Application	Size	O.D., in.	Load Range	Ply Rating	Design Press., psi	Max Press., psi	Max Load at Design press., psi
Passenger car ↓	AR78-13	23.36	B* ↓	4 ↓	26 ↓	32 ↓	940 1240 940 1650 940 1970
	ER78-13	25.16					
	AR78-14	23.98					
	JR78-14	27.94					
	AR78-15	24.70					
Light truck ↓	HR78-15	29.92	C/D/E D/E/F E/F/G F/G/H	6/8/10 8/10/12 10/12/14 12/14/16	50/65/80 50/65/80 85/100/115 90/105/120	** ↓	1430/1690/1920 3000/3550/4045 4610/5150/5670 5780/6430/7030
	6.00R16LT	28.80					
	12.00R16.5LT	32.20					
	9.00R20	40.10					
Heavy truck ↓	11.00R24.5	43.48					

*While C and D ranges exist, their usage is uncommon.

**Pressure limit is determined by the rim rating.

Data Source: 1979 Yearbook, The Tire and Rim Association, Inc.

Table A-2
AVERAGE DAILY TRUCK USAGE IN 11 URBAN AREAS*

TRUCK CLASS	TRUCKS MAKING TRIPS NUMBER	TRUCKS MAKING TRIPS %	DAILY TRIPS NUMBER	DAILY TRIPS %	DAILY TRUCK-MILES NUMBER	DAILY MILEAGE PER TRUCK PER TRIP	DAILY TRIPS PER TRUCK ¹
LIGHT $\leq 10,000$ LB	72,989	71.8	608,606	67.7	2,075,660	28.4	8.3
MEDIUM-HEAVY >10,000 LB	28,691	28.2	289,810	32.3	1,104,742	36.5	10.1
TOTAL	101,680	100.0	898,410	100.0	3,180,402	31.3	8.8

*REF. 15

¹These values are for trucks making trips on a typical weekday. When related to all trucks registered in the urban area, the average is 5.9 trips per day, since a proportion of the registered trucks are idle on any given day.

NOTE: The values are summations of trip values for the 11 areas shown in source.

SOURCE: Comprehensive transportation studies by Wilbur Smith and Associates in Albuquerque, New Mexico; Baltimore, Maryland; Baton Rouge, Louisiana; Columbia, South Carolina; Little Rock, Arkansas; Manchester, New Hampshire; Monroe, Louisiana; Richmond, Virginia; Sioux Falls, South Dakota; and Winston-Salem, North Carolina.

From these figures it can be seen that truck usage, by and large, is very similar to that for passenger cars. These trucks blend into the flow of the urban traffic and experience similar accels/decels and cruise speeds. As a consequence it appears reasonable to assume that, except for the difference in the magnitudes of the forces and torques involved, tire wear schedules for truck and passenger car tires are not unlike.

Tread rubber in passenger car tires is principally a blend of synthetic rubbers with little to no natural rubber (NR) used. Typically, the blend ratio is 60% styrene butadiene copolymer (SBR) and 40% polybutadiene (BR) together with carbon black filler. Truck tires use SBR and BR together with NR in the tread rubber. NR is used here because it has very low hysteretic losses resulting in less heat buildup which can be destructive in truck applications. Tread rubber hardness, as measured by the Shore number, typically varies in the range from 55 to 65 for both passenger car and truck tires (hardness increases with the numerical value of the Shore number).

One of the important characteristics of the tire rubber that affects wear is the coefficient of friction. Of the three rubbers used in tread compounding, SBR has the highest coefficient of friction when compared to BR and NR. Reference 13 concludes, on the basis of experimental data, that materials with a higher coefficient of friction (like SBR) tend to be snagged by roadway asperities and form roll patterns in cornering, leading to fatigue type wear on concrete highways. Low friction materials, like BR and NR, tend to slide more readily over the asperities, to break cleanly and form a fine granular texture when highly stressed. On coarse-texture surfaces (gravel), all materials snag on the asperities, and the wear surfaces of each are similar in appearance.

Another area of difference between passenger car and truck tires is the contact pressures in the footprint. Pressure distributions in the footprint are very uneven and depend on load, inflation pressure, tire construction, etc. As a rule of thumb, the minimum contact pressure can be taken as equal to the inflation pressure. Thus while higher contact pressures will lead to higher cyclic stresses and heat buildup, thermal degradation of tread rubber has not been shown to be a factor in tread wear* (2, 3). Additionally, localized stresses in tread rubber in contact with road asperities are usually below the destructive limit so that the tread rubber does not suffer irreversible damage (11). There are no known data on the effects of contact pressure on tire wear except for the known fact that regions of high contact pressure in the tire patch usually correspond to areas of higher wear.

To summarize, tires designed for truck use are characterized by different constructions, sizes, loads and pressures when compared to passenger car tires. Truck tires use different tread rubber formulations which result in a coefficient of friction lower than that for automobile tires. On fine to medium textured roads, such as found in urban areas, the lower friction material will tend to abrade cleanly forming smaller particulates. On the other hand, the higher

* Under normal operating conditions.

friction material, more typical of automobile tires, will tend to form larger particles due to tearing and roll formation. Usage patterns among trucks and passenger cars in urban areas are similar. Consequently, the particulates generated by truck tires may be expected to be similar to those produced by passenger car tires except that the size distribution may favor the smaller size at the expense of the large. In terms of wear rates, it has been estimated that wear rates for truck tires, on a grams per mile basis should be slightly less than for bias-ply automobile tires (2). Supporting data are not available.

APPENDIX B

VALIDATION OF THE SEM TECHNIQUE FOR IDENTIFYING RUBBER PARTICULATES

The scanning electron microscope was used in two modes of operation in the analysis of the tire wear particulates. Using secondary electron emission detection, photographs were taken at magnifications up to 20,000X of the smaller particulates to show their size, shape and structure at a high level of detail and with excellent depth of field. In addition, by utilizing the x-rays emitted by the specimens when bombarded by high-energy electrons in an energy dispersive x-ray analyzer, an x-ray spectrum is obtained which permits the identification of the elemental composition. All elements with an atomic number, Z , equal to 11 and larger, can be identified in this manner.

With an element identification capability restricted to $Z \geq 11$, it is clear that the SEM cannot be used to identify such organic materials as rubber in a direct fashion. In the formulation of tread rubber compounds, various additives are included to achieve desired characteristics. Among these additives are sulfur, S, ($\approx 1\%$) and zinc oxide, ZnO , ($\approx 1.5\%$). Tests were therefore performed to ascertain the efficacy of identifying rubber particles, in the presence of contaminants, by their sulfur and zinc "signatures." Anticipating that the debris from the Safety-Walk surface would represent the principal source of contaminant in the tire wear samples, a piece of new (unused) Safety-Walk was used as a control.

SEM specimens must be electrically conducting. Specimens that are normally nonconducting are coated with gold (Au)/palladium (Pd) using vapor deposition techniques. A photograph of a portion of new Safety-Walk surface is shown at a magnification of 30X in Figure B-1a. This material is in an "as received" condition. The sharp asperities shown are normally blunted by a stoning operation that is performed on the Safety-Walk surface after it is installed on the TIRF belt. The lower photograph (Figure B-1b) reproduces the x-ray spectrum corresponding to an integrated scan of the Safety-Walk surface. Silicon (Si) and magnesium (Mg) are seen to be the principal identifiable* constituents of the Safety-Walk surface; the gold and palladium peaks are due to the conductive film applied to the specimen.

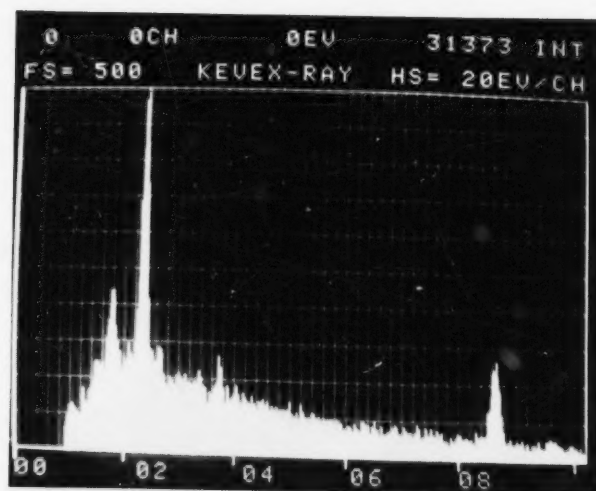
A very large rubber particle, worn from a tire during a test, is shown in Figure B-2a at a magnification of 100X. The lacy, sponge-like appearance is very characteristic of the large rubber particulates. The x-ray spectrum of the rubber particle is depicted in Figure B-2b and exhibits the very prominent peaks of sulfur and zinc. This result demonstrated that adequate sensitivity was available for the identification of rubber particles in a sample of unknown composition by the simultaneous presence of the elements sulfur and zinc. Note the presence of silicon in the x-ray spectrum. Apparently, a fragment of a silicon dioxide grit was imbedded in this particle of rubber.

* The Safety-Walk is composed mainly of organic materials except for the silicon dioxide grits which are bonded with a polyurethane composed of aromatic polyisocyanides and polyamines.



(a)

MAGNIFICATION = 100X



(b)

Figure B-2 SEM PHOTOGRAPH OF A LARGE RUBBER PARTICLE AND ITS ANNOTATED X-RAY SPECTRUM

APPENDIX C

THE CALSPAN TIRE RESEARCH FACILITY (TIRF)

A photograph of the TIRF facility is shown as Figure C-1; a dimensional view of the facility is shown in Figure C-2. The primary features of the machine are:*

Tire Positioning System

The tire, wheel, force sensing balance and hydraulic motor to drive or brake the tire are mounted in the movable upper head. The head provides steer, camber and vertical motions to the tire. These motions (as well as vertical loading) are servocontrolled and programmable for maximizing test efficiency. The ranges of the position variables, the rates at which they may be adjusted and other information are shown in Table C-1.

Roadway

The 28-inch wide roadway is made up of a stainless steel belt covered with material that simulates the frictional properties of actual road surfaces. The belt is maintained flat to within 1 to 2 mils under the tire patch by the restraint provided by an air bearing pad which is beneath the belt in the tire patch region. The roadway is driven by one of the two 67-inch diameter drums over which it runs. The road speed is servocontrolled; it may be programmed to be constant or varied.

The surfaces usually used are "Safety-Walk".** These surfaces have excellent microtexture giving a wet skid number*** of about 60 in the untreated condition. The surfaces are honed to reduce the wet skid number to lower values (typically surfaces of skid number 50 and 30 are used).

A unique feature of TIRF is the ability to carry out tests under wet road conditions. A two-dimensional water nozzle spans the roadway. This nozzle has an adjustable throat which can be set to the desired water depth. The flow through the nozzle is then varied by controlling the water pressure. At each test condition the water film is laid on tangential to the belt at belt velocity. The film thickness may be varied from as low as 0.005 inches up to 0.4 inches.

* A more complete description of this facility will be found in Reference 6.

** Manufactured by the 3M Company.

*** At 40 mph and 0.020-inch water depth using the ASTM E-501 Standard Pavement Traction Tire.

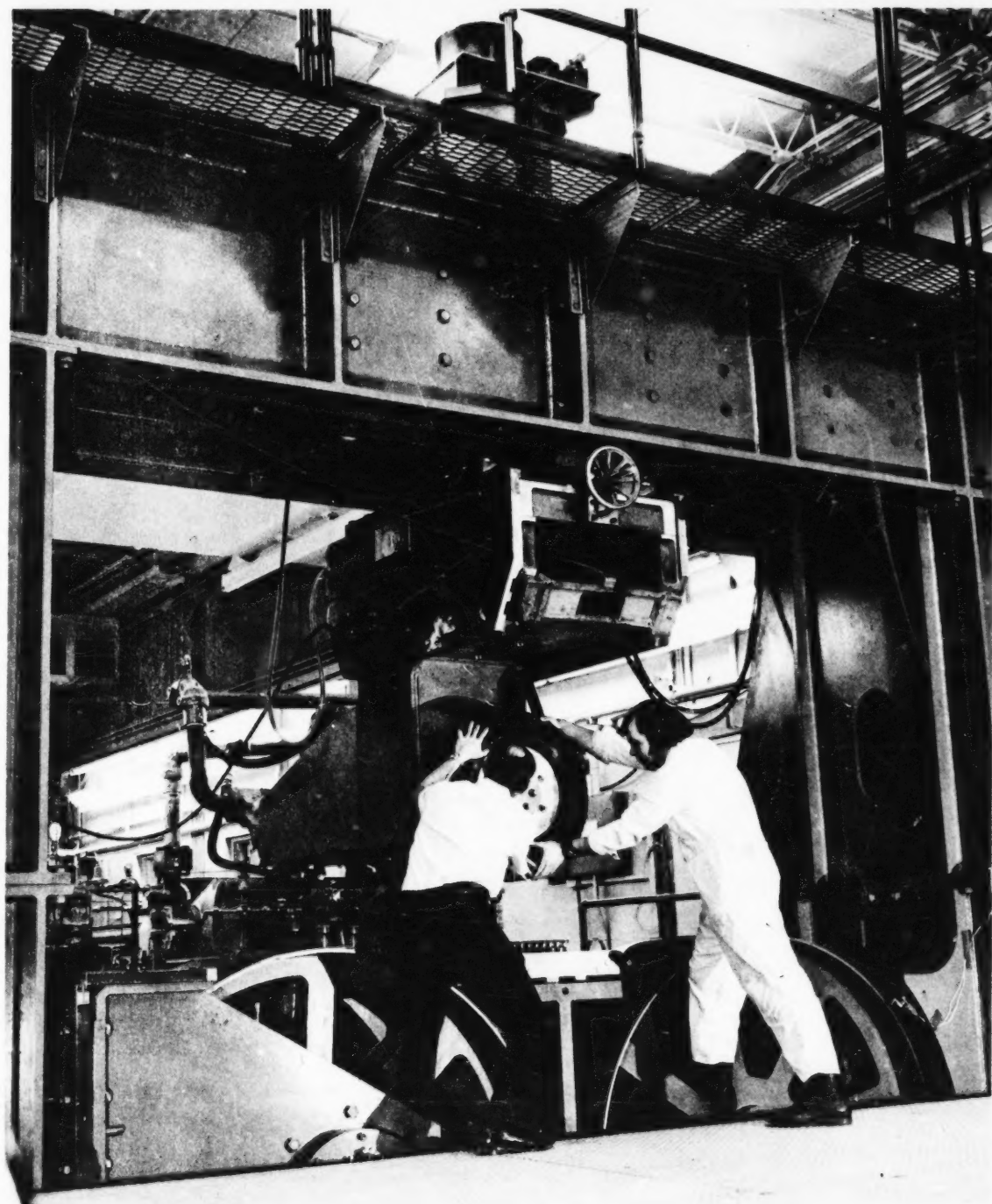


Figure C-1 CALSPAN TIRE RESEARCH FACILITY (TIRF)

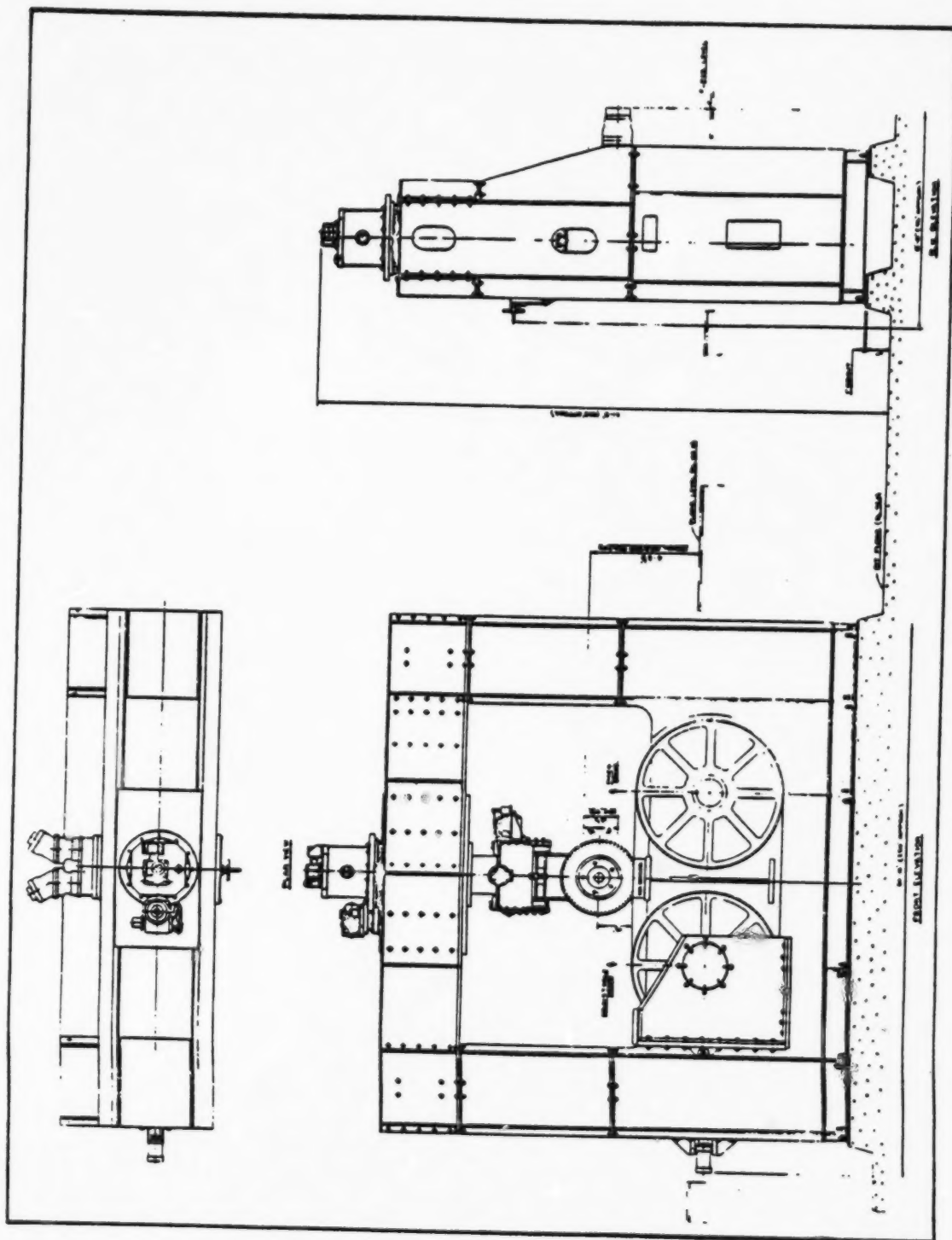


Figure C-2 TIRE RESEARCH MACHINE

TABLE C-1

TIRF CAPABILITIES

CHARACTERISTIC	RANGE
TIRE SLIP ANGLE (α)	$\pm 30^\circ$ *
TIRE INCLINATION ANGLE (γ)	$\pm 30^\circ$ **
TIRE SLIP ANGLE RATE ($\dot{\alpha}$)	$10^\circ/\text{sec}$
TIRE INCLINATION ANGLE RATE ($\dot{\gamma}$)	$7^\circ/\text{sec}$
TIRE LOAD RATE (TYPICAL)	2000 lb/sec
TIRE VERTICAL POSITIONING RATE	$2''/\text{sec}$
ROAD SPEED (V)	0-170 mph
TIRE OUTSIDE DIAMETER	Up to 46"
TIRE TREAD WIDTH	24" MAX.
BELT WIDTH	28"

TABLE C-2

BALANCE SYSTEM CAPABILITY

COMPONENT	PASSENGER CAR TIRE BALANCE	TRUCK TIRE BALANCE
TIRE LOAD	4,000 lb	12,000 lb
TIRE TRACTIVE FORCE	$\pm 4,000$ lb	$\pm 9,000$ lb
TIRE SIDE FORCE	$\pm 4,000$ lb	$\pm 8,000$ lb
TIRE SELF ALIGNING TORQUE	± 500 lb ft	$\pm 1,000$ lb ft
TIRE OVERTURNING MOMENT	$\pm 1,000$ lb ft	$\pm 2,000$ lb ft
TIRE ROLLING RESISTANCE MOMENT	± 200 lb ft	± 400 lb ft

*Can be Increased to 90° with Special Setup.

**Can be Increased to 60° with Special Setup.

Tire-Wheel Drive

A drive system which is independent of the roadway drive is attached to the tire-wheel shaft. This separate drive allows full variation of tire slip both in the braking and driving modes. The tire slip ratio, referenced to road speed, is under servocontrol.

Balance System*

A six-component strain gage balance surrounds the wheel drive shaft. Three orthogonal forces and three corresponding moments are measured through this system. A fourth moment, torque, is sensed by a torque link in the wheel drive shaft. The load ranges of the basic passenger car and truck tire balances are shown in Table C-2. Transfer of forces and moments from the balance axis-system to the conventional SAE location at the tire-roadway interface is in the data reduction computer program.

System Operation

Data Acquisition Program (DAP) Control

The data acquisition program (DAP) is a software system which controls machine operation and logs data during tests. DAP controls test operations by means of discrete setpoints which are generated in the computer by the program. These setpoints are sent to the machine servos which respond and establish tire test conditions. After the setpoints are sent to the servos, a delay time is provided which starts after the machine variables have reached a steady state value within predetermined tolerances. This allows the system to stabilize before data are taken. After data are taken, the next set of test conditions is established and testing continues.

One or two variables can be changed during DAP testing. The other test parameters are kept fixed throughout the test. Up to twenty data points can be used for each variable in a run.

A data reduction program is used to operate on the raw data collected during testing. These new data are reduced to forces and moments in the proper axis system, and all variables are scaled to produce quantities with engineering units. Raw and reduced data are temporarily stored in a disc file. Both reduced and raw data can be transferred to magnetic tape and maintained as a permanent record.

Reduced data points can be listed and plotted, and curves can be fitted to the points. All of the standard Calspan plots can be generated from DAP test data.

* More detailed information on the balance systems and their calibration may be found in Reference 6.

Data lists and plots are displayed on the screen of a CRT console. Hard copies of this information can be made from this display.

Continuous Sampling Program (CSP) Control

The continuous sampling program (CSP) is a software system which controls machine operation and continuously logs data during tests. Test variables can be constant or changed at rapid rates. One or all variables can be changed during a test. Data can be sampled at rates up to 100 samples per second. Pauses are used so that data can be logged during desired intervals of the test.

CSP testing can be conducted quickly which in turn reduces tire wear during severe tests. The high rate of data sampling also permits limited dynamic measurements to be made.

Two-parameter plots of data can be made. Carpet and family plots of test data cannot be made with this program at the present time. CSP data will also reflect time effects if tire characteristics are a function of the rate of change of testing variables.

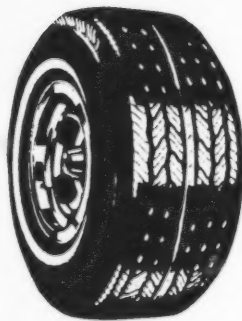
Data reduction is accomplished in a manner similar to that employed in DAP testing.

APPENDIX D

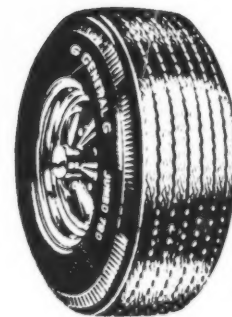
TEST TIRE DATA AND TREAD PATTERNS

The two test tires used on this program were a DR78-14 radial-ply tire and a D78-14 bias-ply tire, both tubeless and with a "B" load range rating. The radial tire was a Dual Steel II which is made with polyester radial plies and a steel-belted construction. The bias tire is a Bias Jumbo 780 and utilizes polyester cords in a cross bias construction. Both tires are products of the General Tire and Rubber Company.

A pictorial representation of these tires is presented in Figure D-1. Both tires use a seven-rib tread design which incorporates many sipes. As is typical of that construction, the radial tire features a relatively open, aggressive tread pattern as compared with that of the bias tire.



GENERAL
DR78-14
DUAL STEEL II
RADIAL



GENERAL
D78-14
JUMBO 780
BIAS

Figure D-1 PICTORIAL VIEWS OF THE TEST TIRES SHOWING THE TREAD PATTERNS